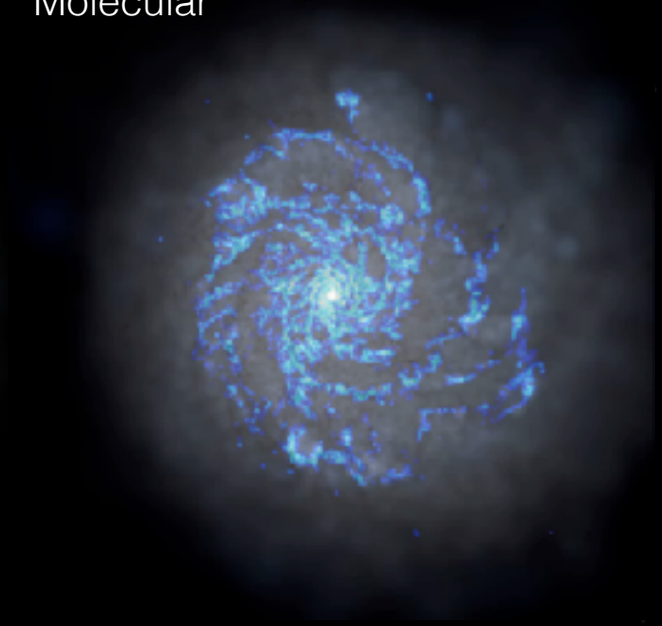
Stars Re-Shaping Galaxies

Observed Starlight

Molecular



Galaxy Merger

X-Rays

Star Formation

Philip F. Hopkins & the FIRE Team

Caltech

Postdocs

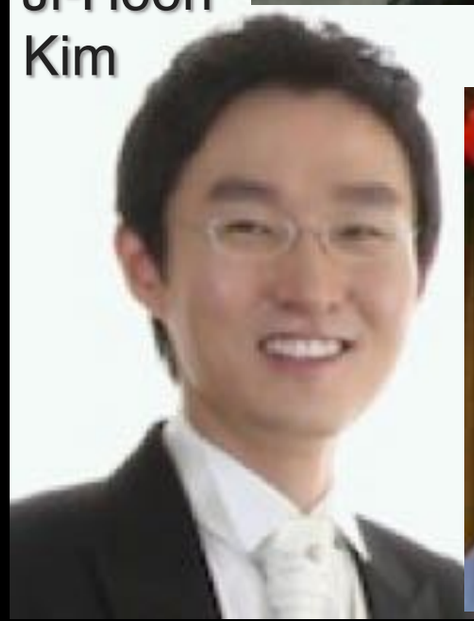
Andrew
Wetzel

Robyn
Sanderson

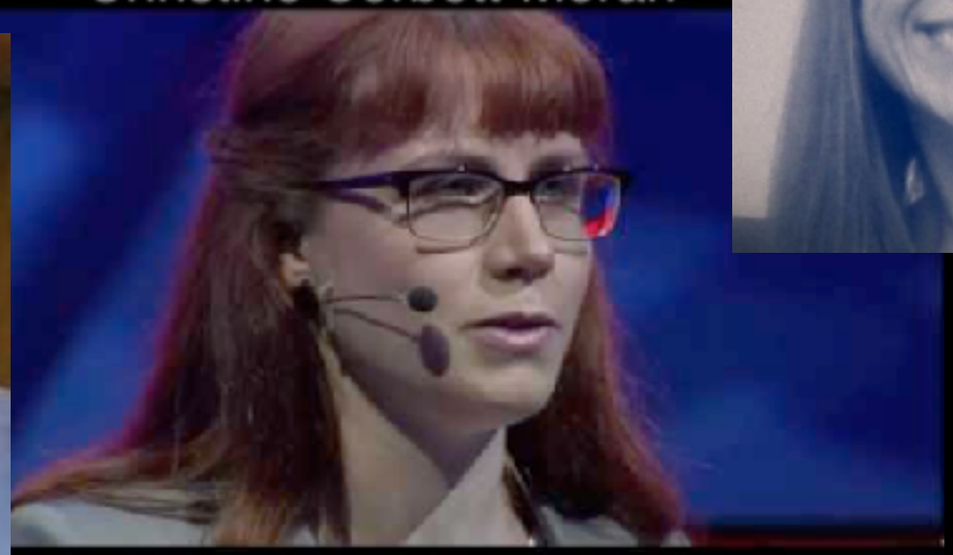
Coral Wheeler

Chris Hayward

Ji-Hoon
Kim

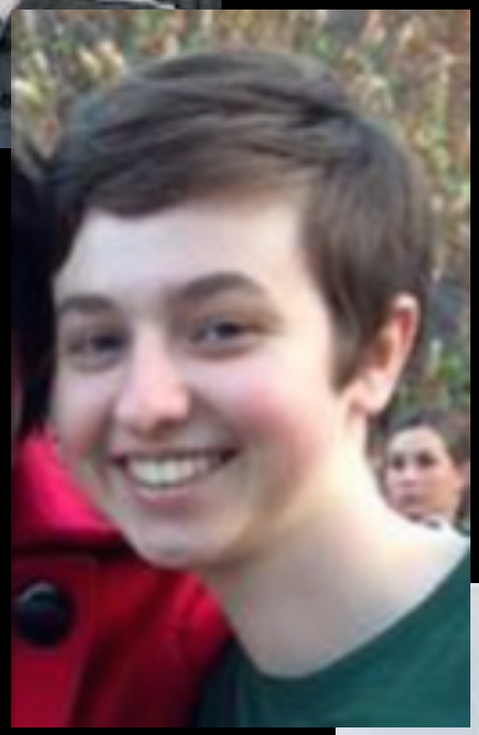


Christine Corbett-Moran

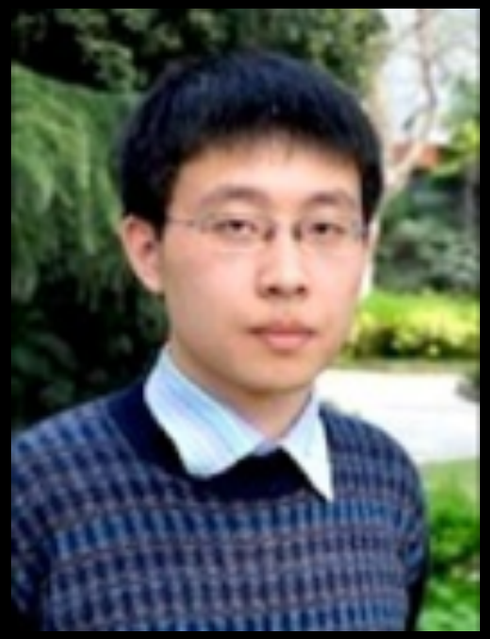


Grad Students

David Guszejnov



Denise Schmitz



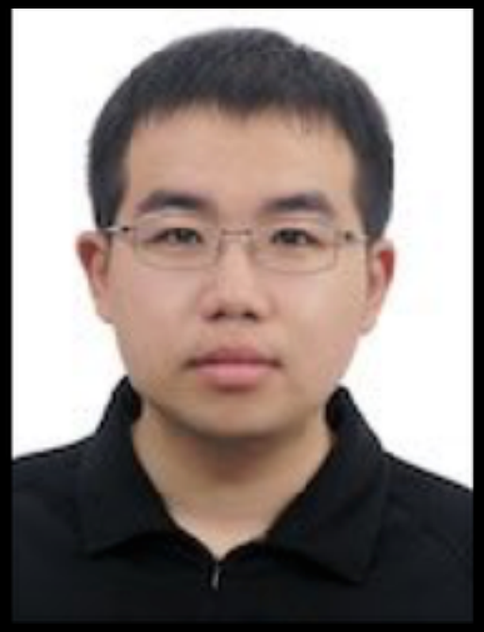
Xiangcheng Ma

Matt Orr

Mike Grudic

Ivanna Escala

Antonija Oklopcic



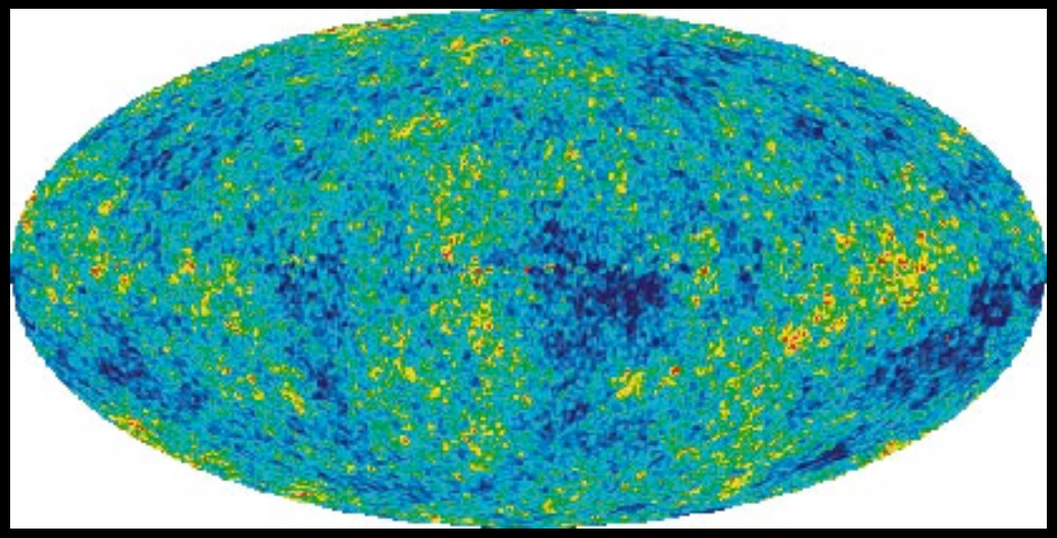
Kung-Yi Su

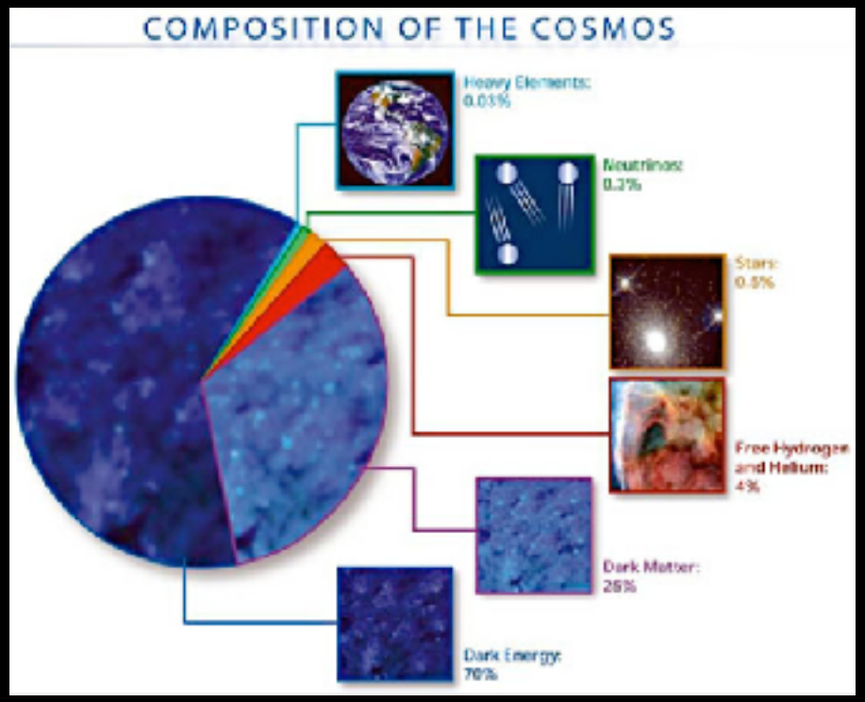
Hannalore Gerling-Dunsmore

What's the Big Picture?

The Big Question:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?





z~1090
(t~400,000 yr)

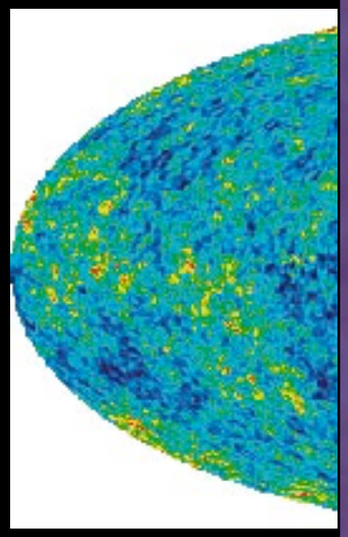
?

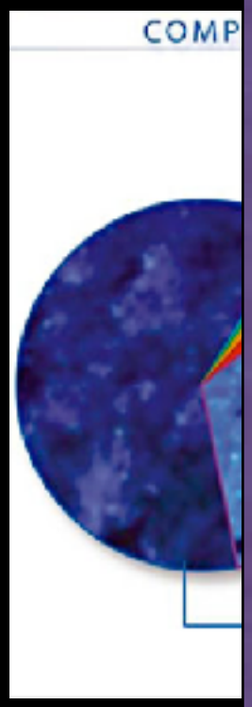
Today

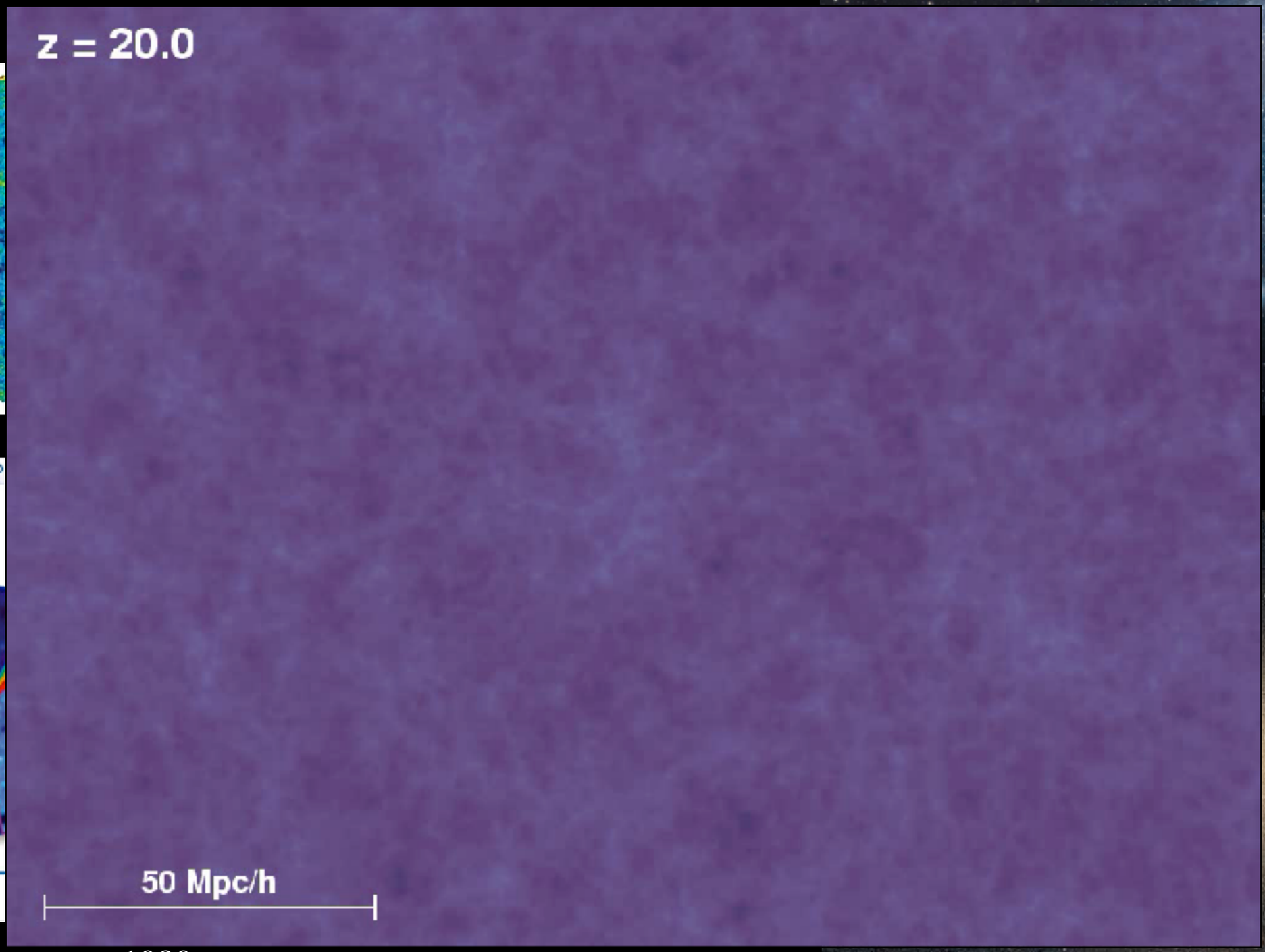
The Big Question:

HOW DO WE GO FROM BIG BANG TO MILKY WAY?

Today



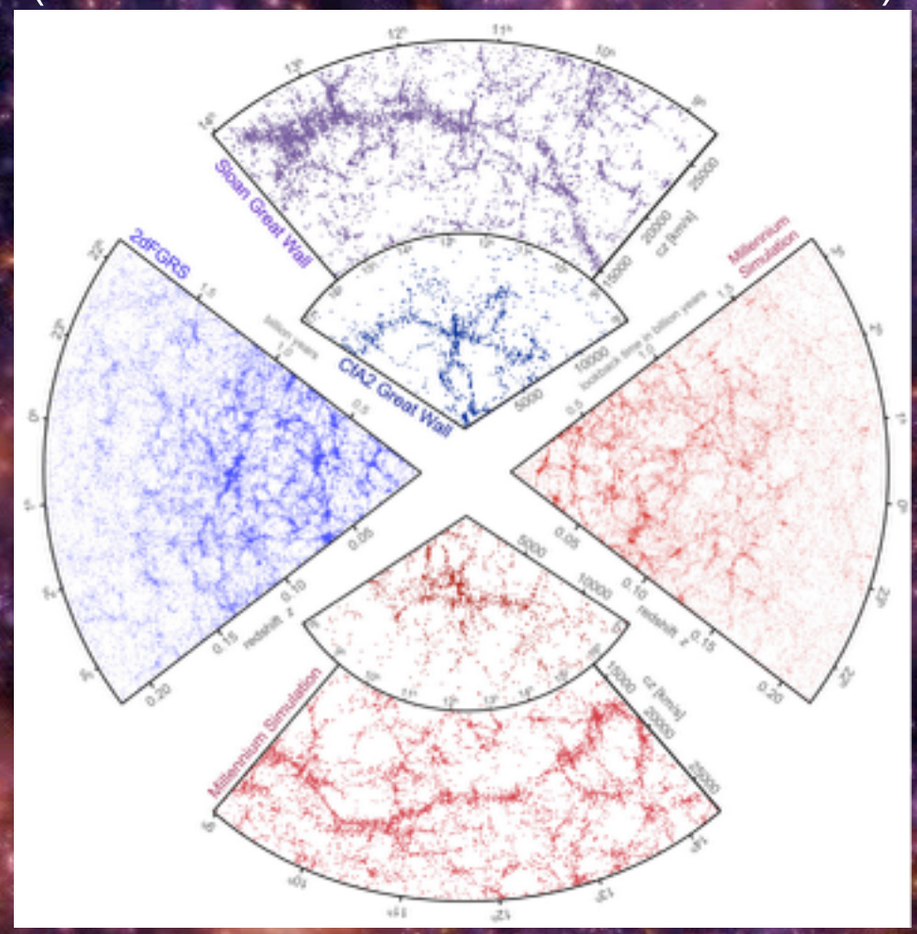




z~1090
(t~400,000 yr)

Large scales: Gravity +
Dark Matter / Energy Works!

Observations vs Theory
(SDSS vs Millennium Simulation)

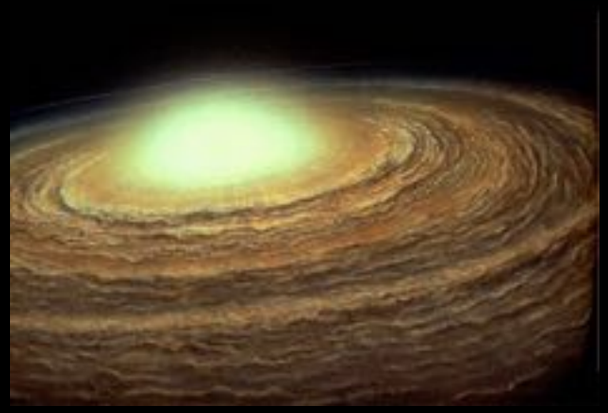


Our work:

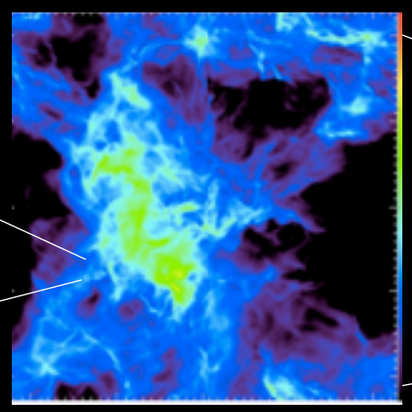
~10^{10} pc
Hubble volume

~10^{7}-10^{8} pc
Clusters, Large-scale structure

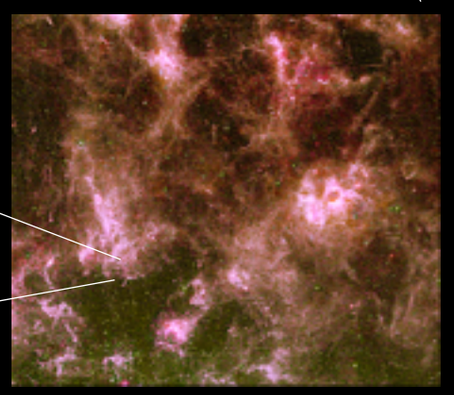
~10^{4-5} pc
Galaxy



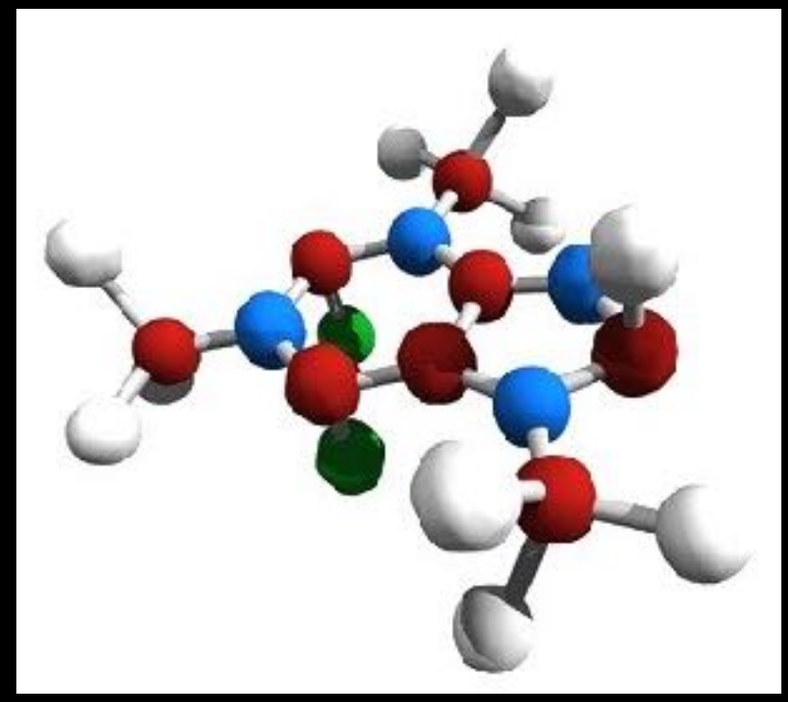
~10^{-5} pc
Stars, protostellar disks



~10^{-2}-10^{0} pc
Cores, clusters,
Supernovae blastwaves

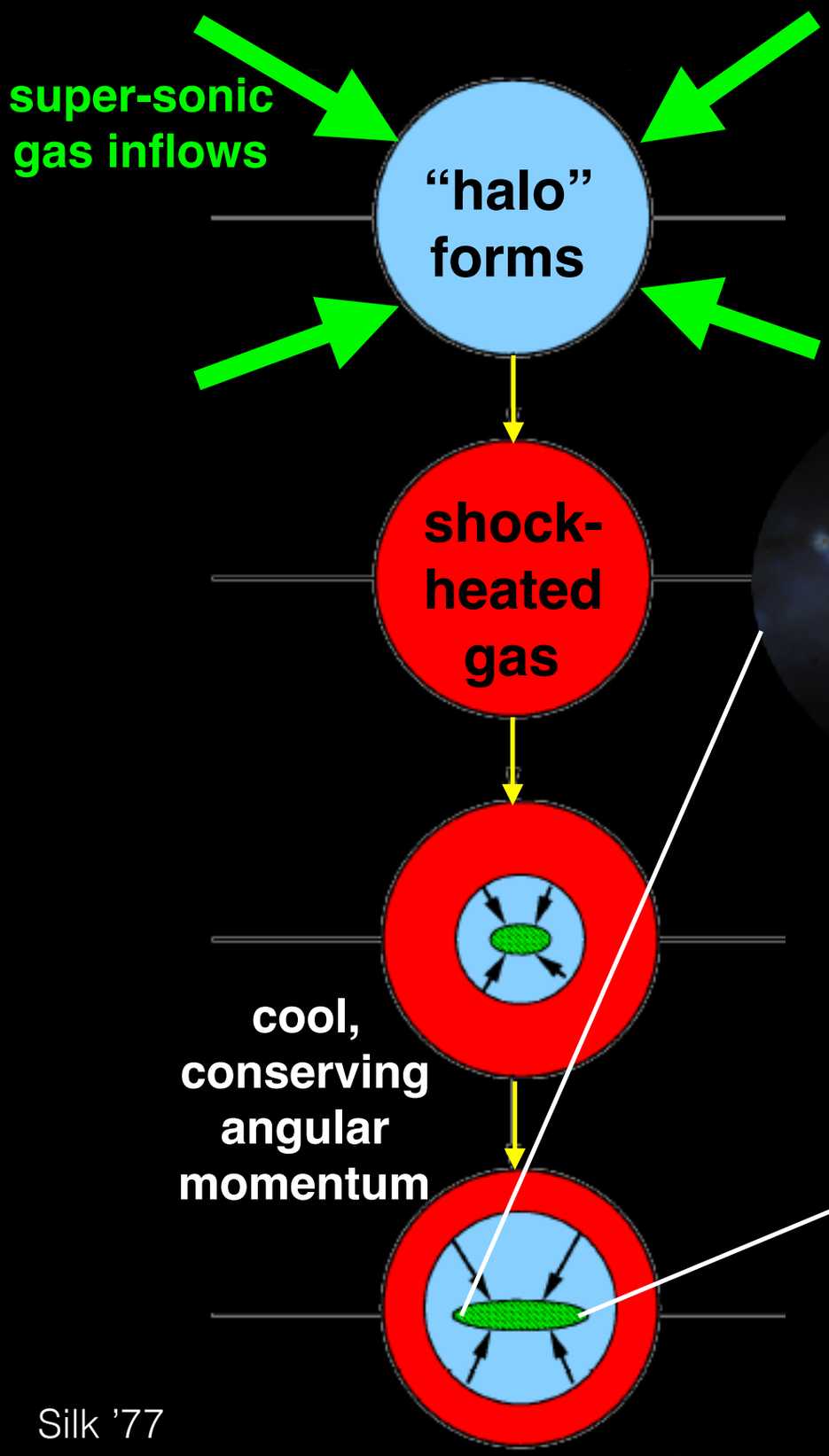


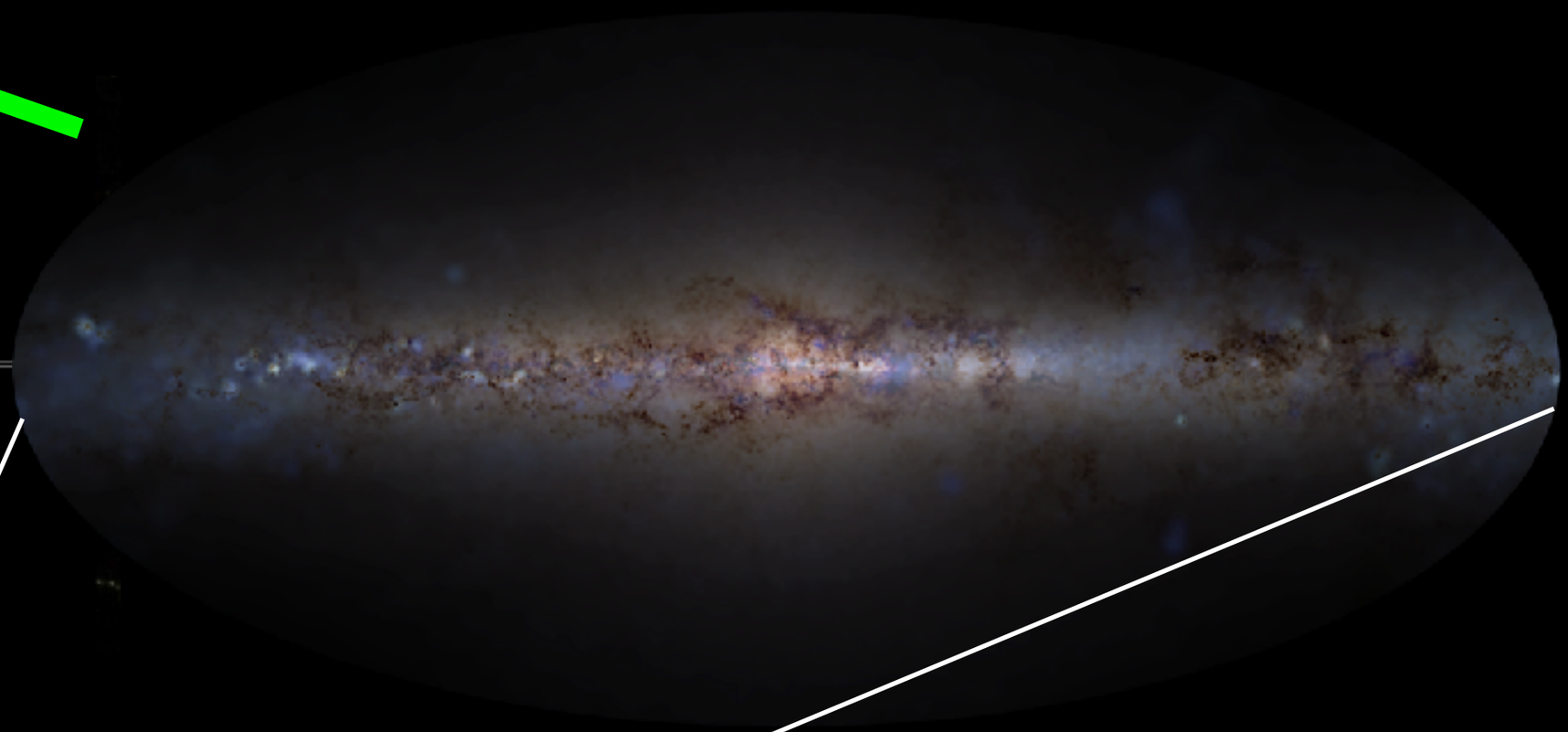
~10^{1}-10^{2} pc
Molecular clouds,
Star-Forming Regions



Add some fluid dynamics and chemistry, and go!

The Basic Picture:





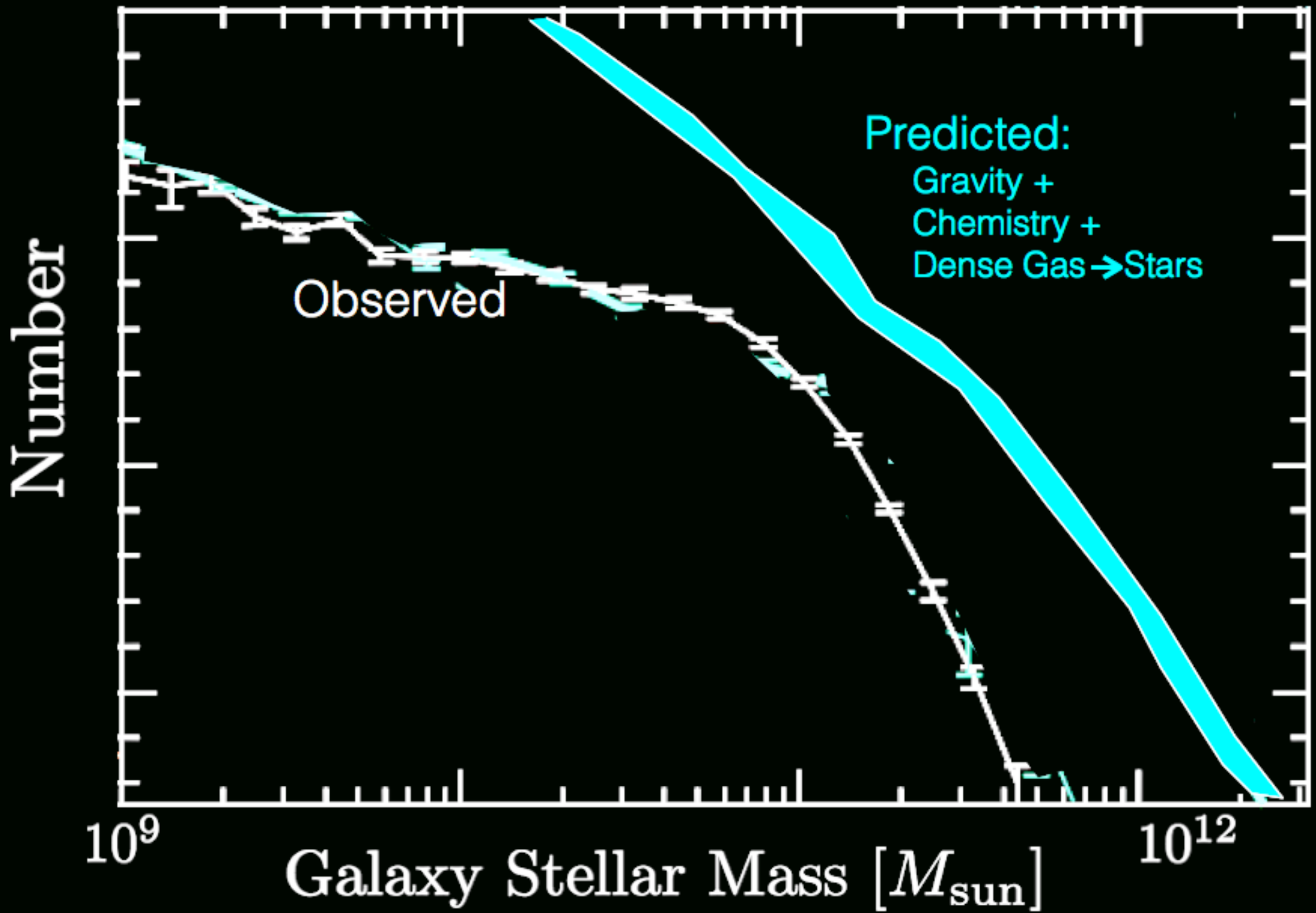
Silk ’77
Binney ’77
Rees & Ostriker ‘77

Done!

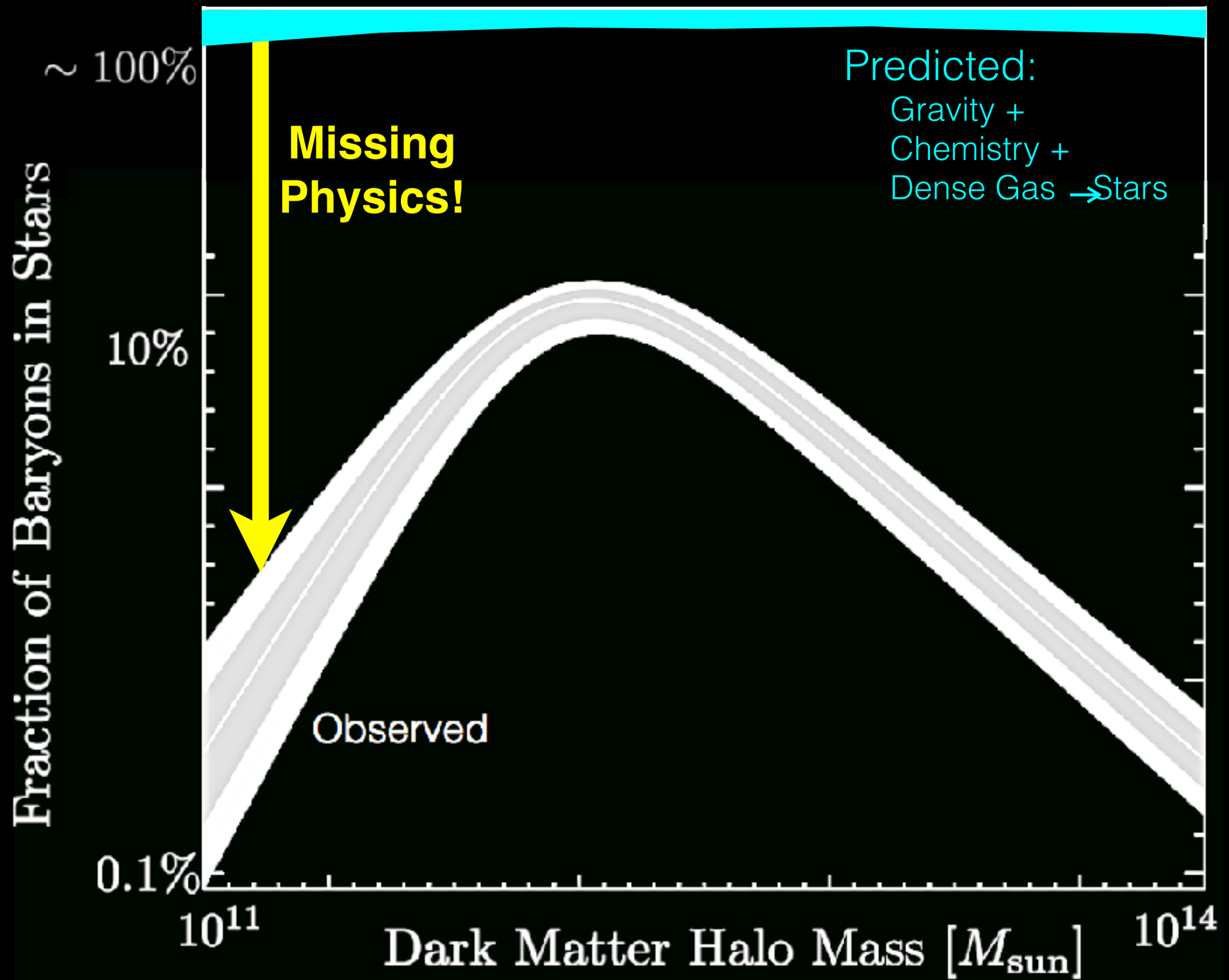
Not so fast…

Problem:

WHY SO FEW GALAXIES & STARS?

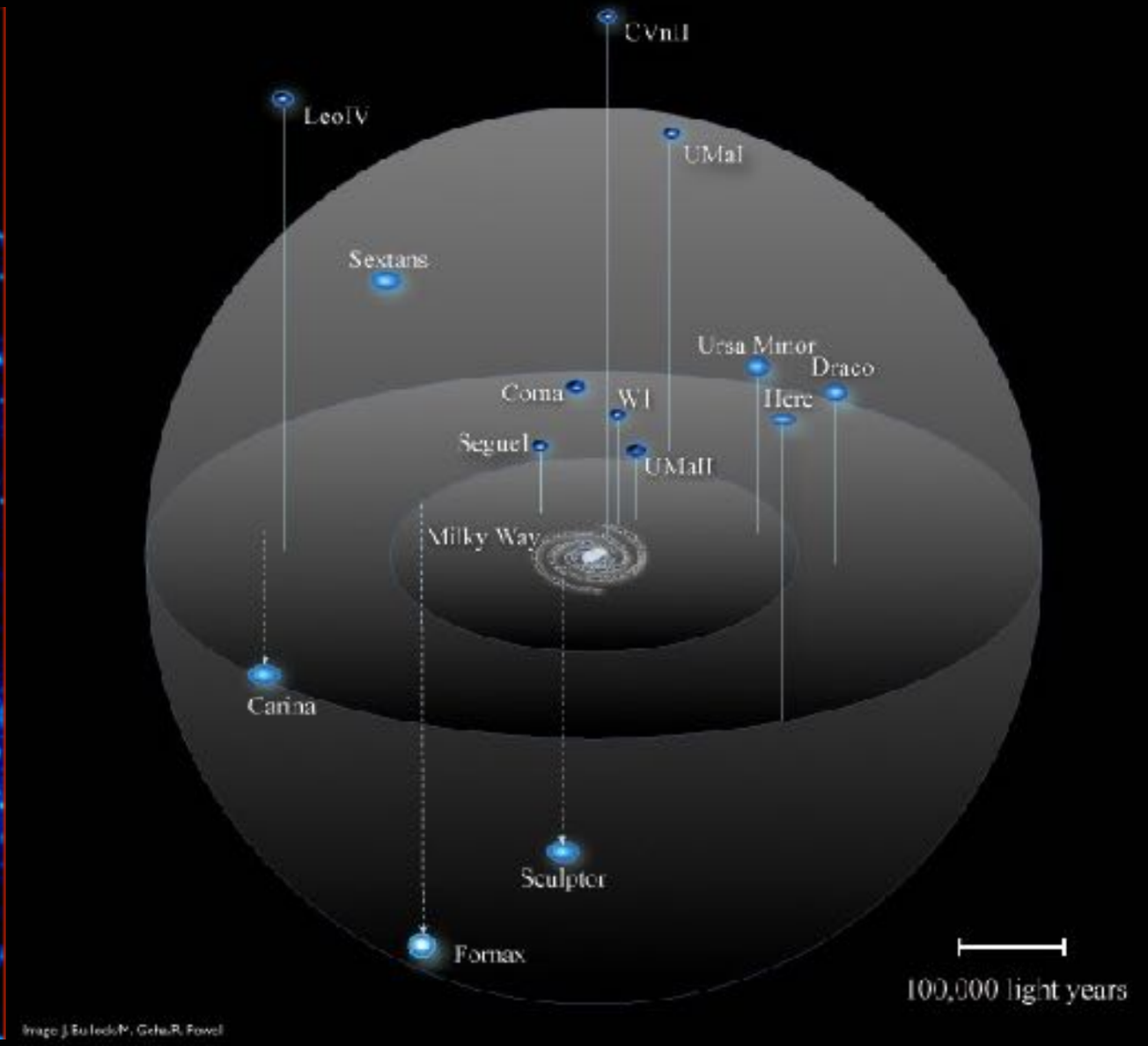


Problem:
WHY SO FEW GALAXIES & STARS?



Problem:
WHERE ARE THE "MISSING SATELLITES"?

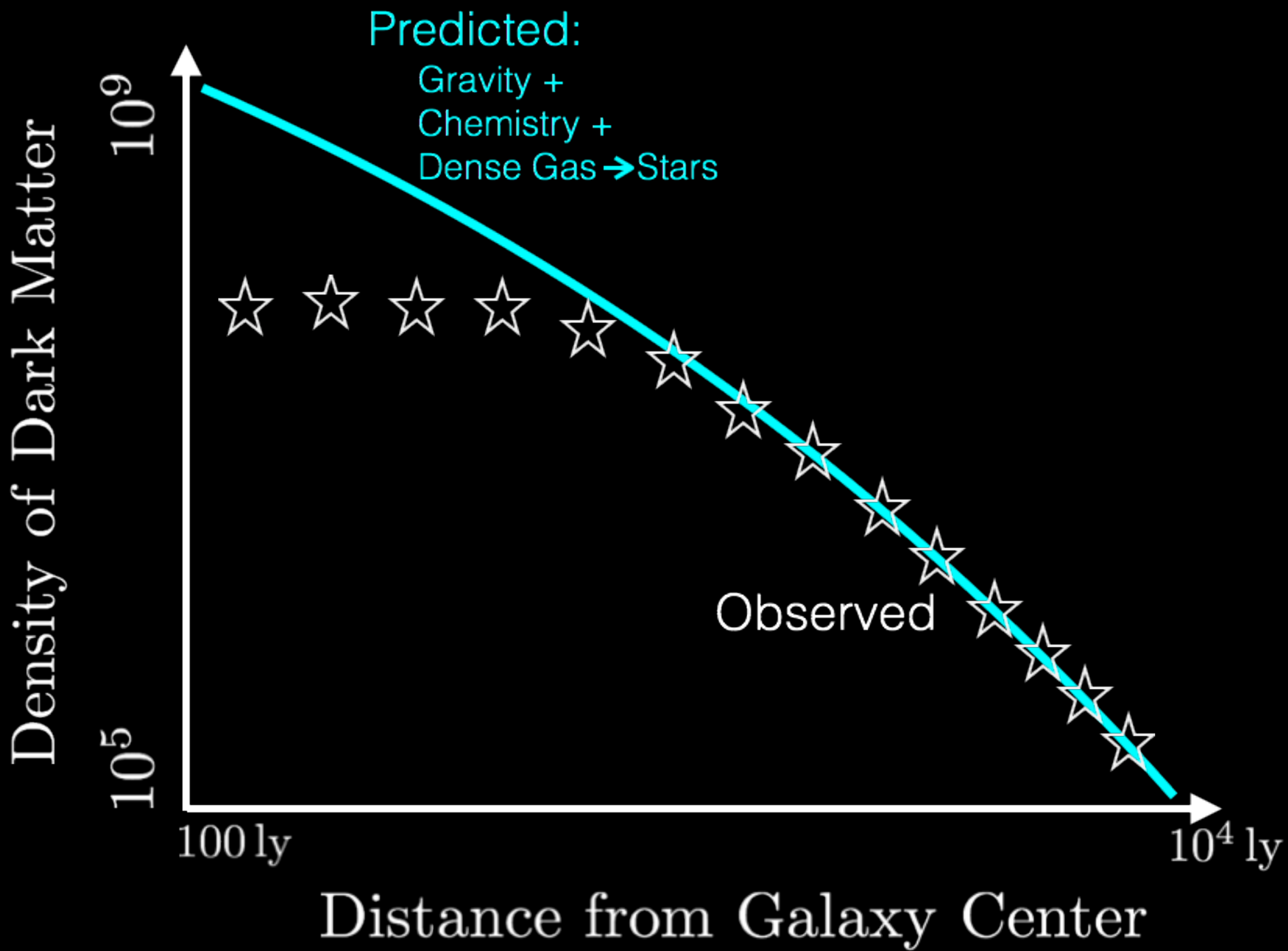
Predicted structure
(dark matter)



Observed
around us

Problem:

WHY ISN'T THERE MORE DARK MATTER?
("CUSP-CORE" or "TOO BIG TO FAIL")



Stars Matter

… Nature hates theorists

~10^{10} pc

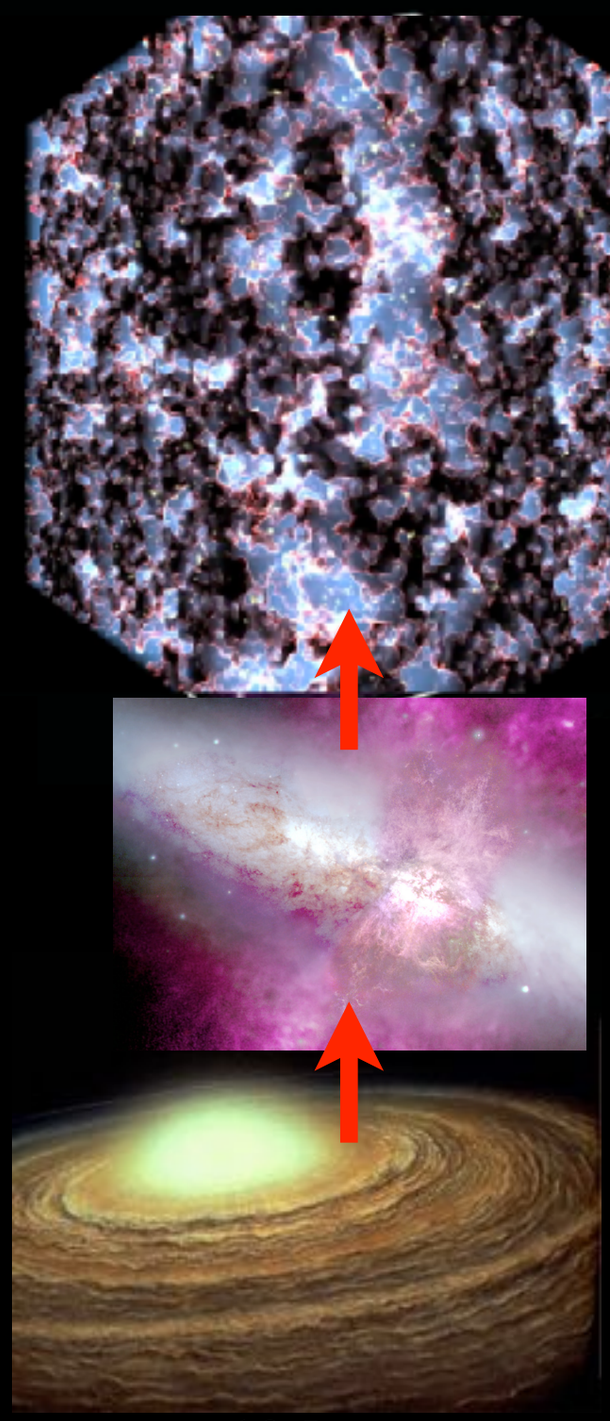
Hubble volume

~10^{7}-10^{8} pc

Clusters, Large-scale structure

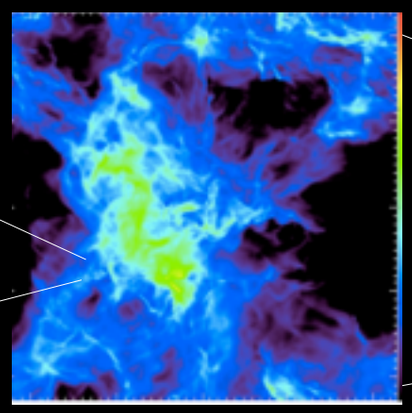
~10^{4-5} pc

Galaxy



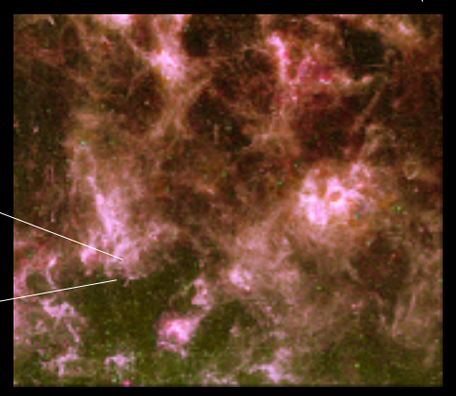
~10^{-5} pc

Stars, protostellar disks



~10^{-2}-10^{0} pc

Cores, clusters,
Supernovae blastwaves



~10^{1}-10^{2} pc

Molecular clouds,
Star-Forming Regions

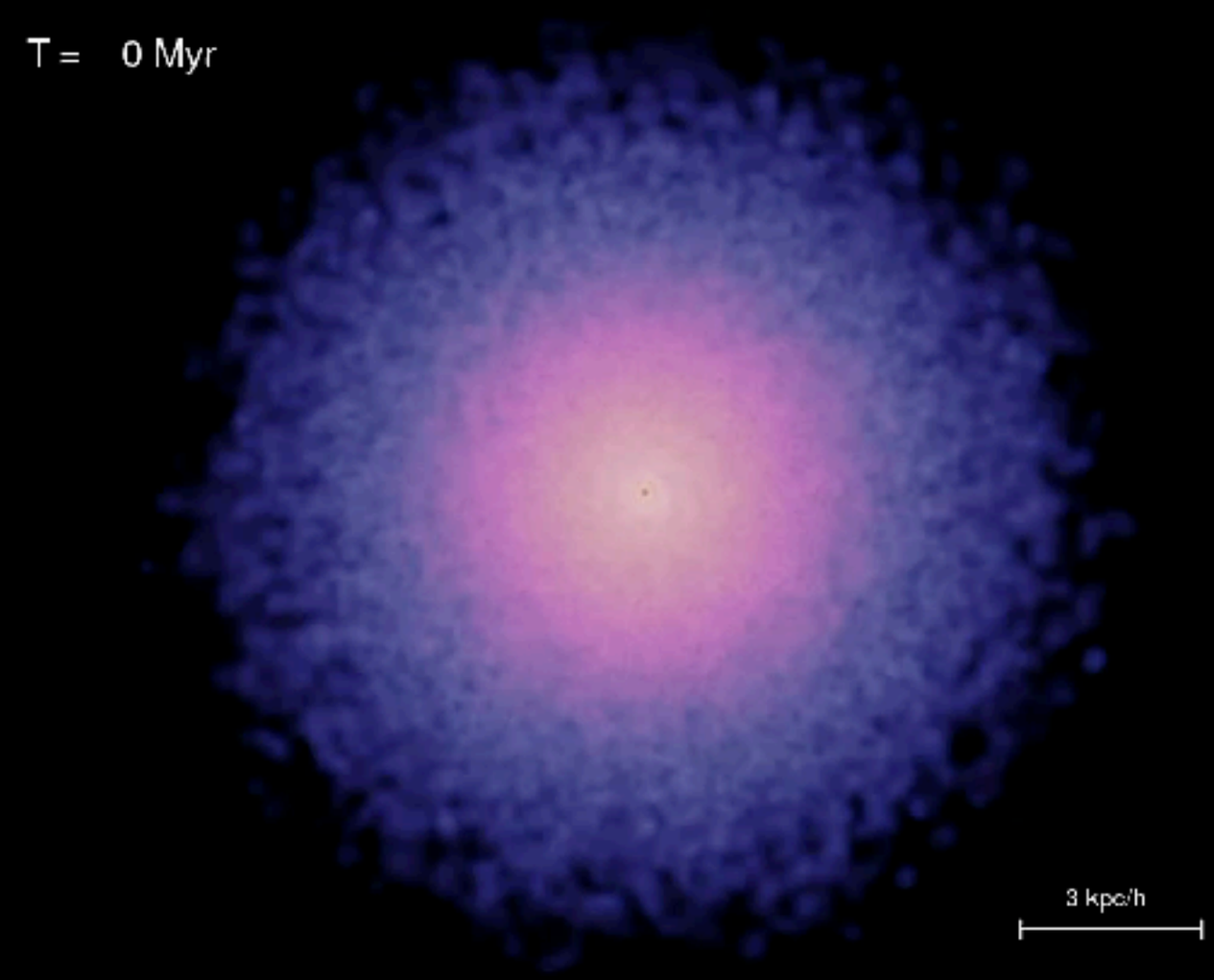
But we know what stars do!

(…well enough…)

Previous “State of the Art”

Resolution:
~kpc
~10^6 M_{sun}

Interstellar Medium:
single, ideal fluid



Winds?
“sub-grid” (cheat a bit)

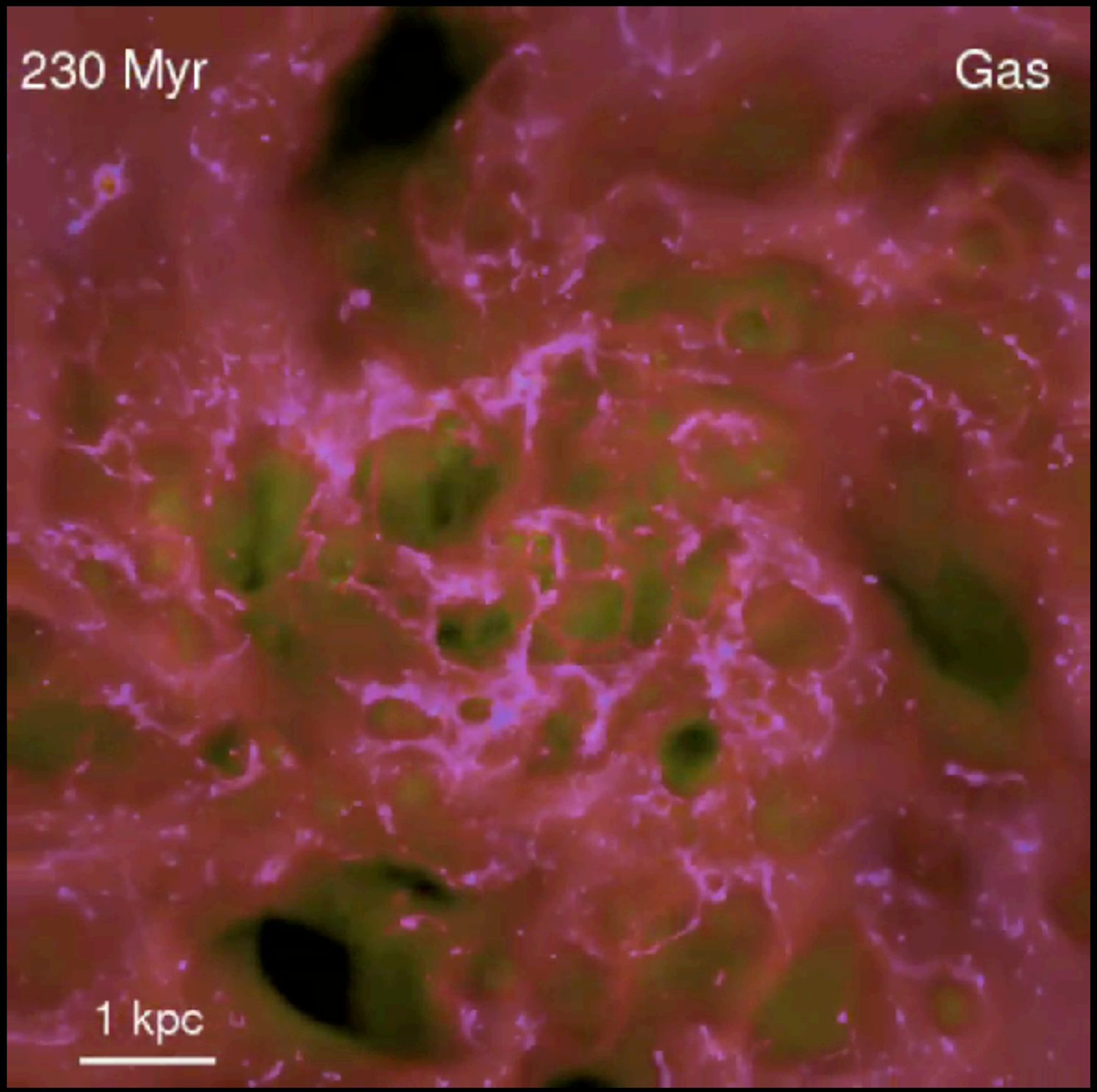
- turn off cooling
- throw out mass “by hand”

$$M_{\rm wind} = ({\rm fudge}) \times M_{\rm stars}$$

e.g. “Illustris”, “OWLS,” “EAGLE,”
…anything I wrote before 2012…

The FIRE Project

Feedback In Realistic Environments



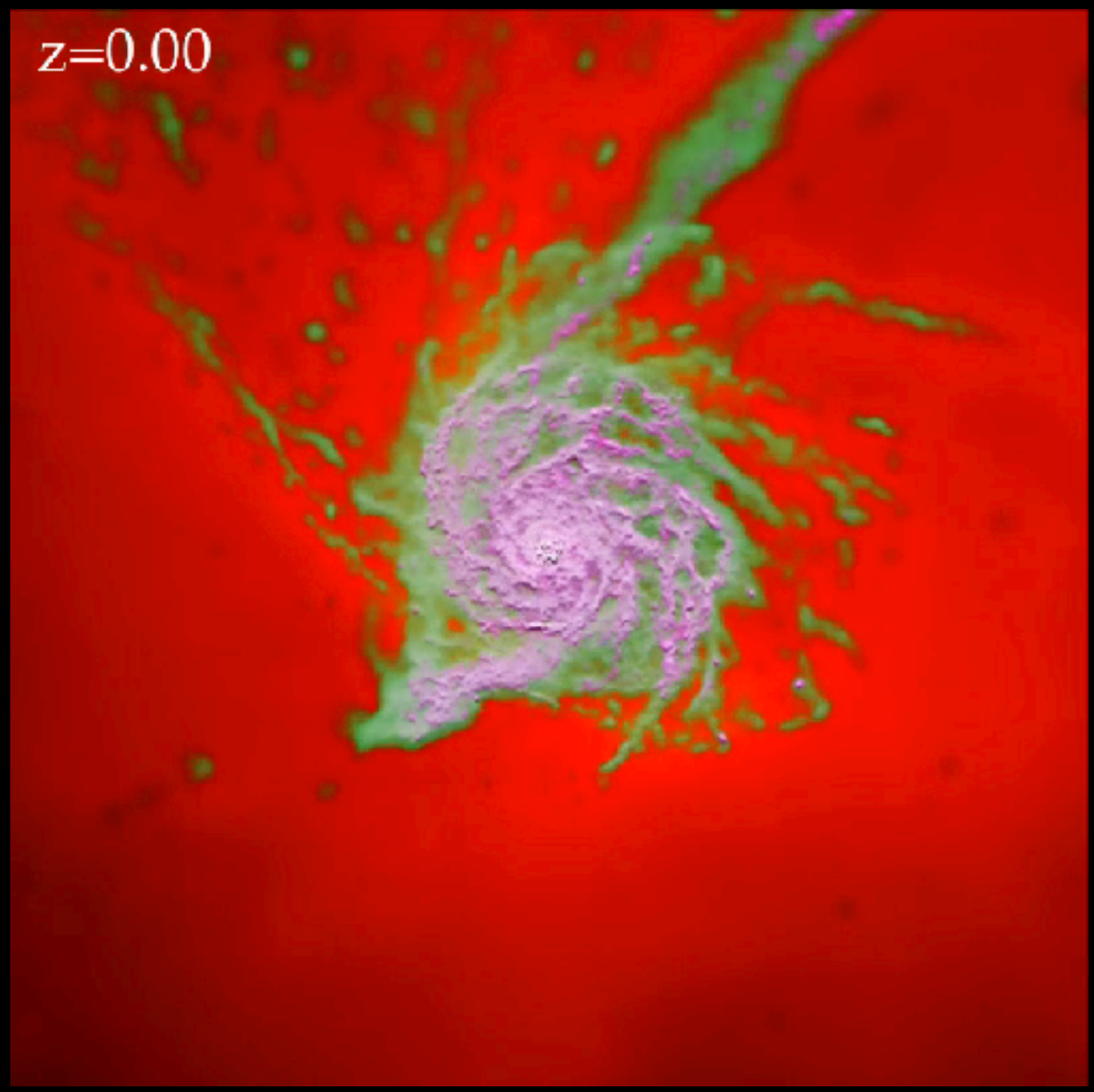
Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10-8000 K)

- Resolution ~pc
  Cooling & Chemistry ~10 - 10^{10} K

- **<u>Feedback:</u>**
  - SNe (II & Ia)
  - Stellar Winds (O/B & AGB)
  - Photoionization (HII regions)
    & Photo-electric (dust)
  - Radiation Pressure (IR & UV)

- now with…
  - Magnetic fields
  - Anisotropic
    conduction & viscosity
  - Cosmic rays

(movies at fire.northwestern.edu)



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

Gas: Magenta: cold $(< 10^4\,K)$

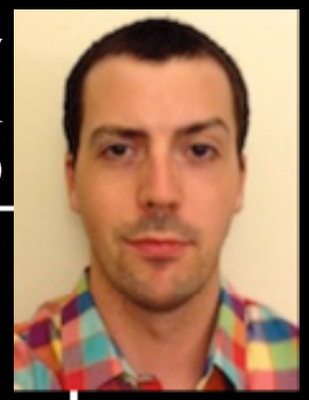
Green: warm (ionized)

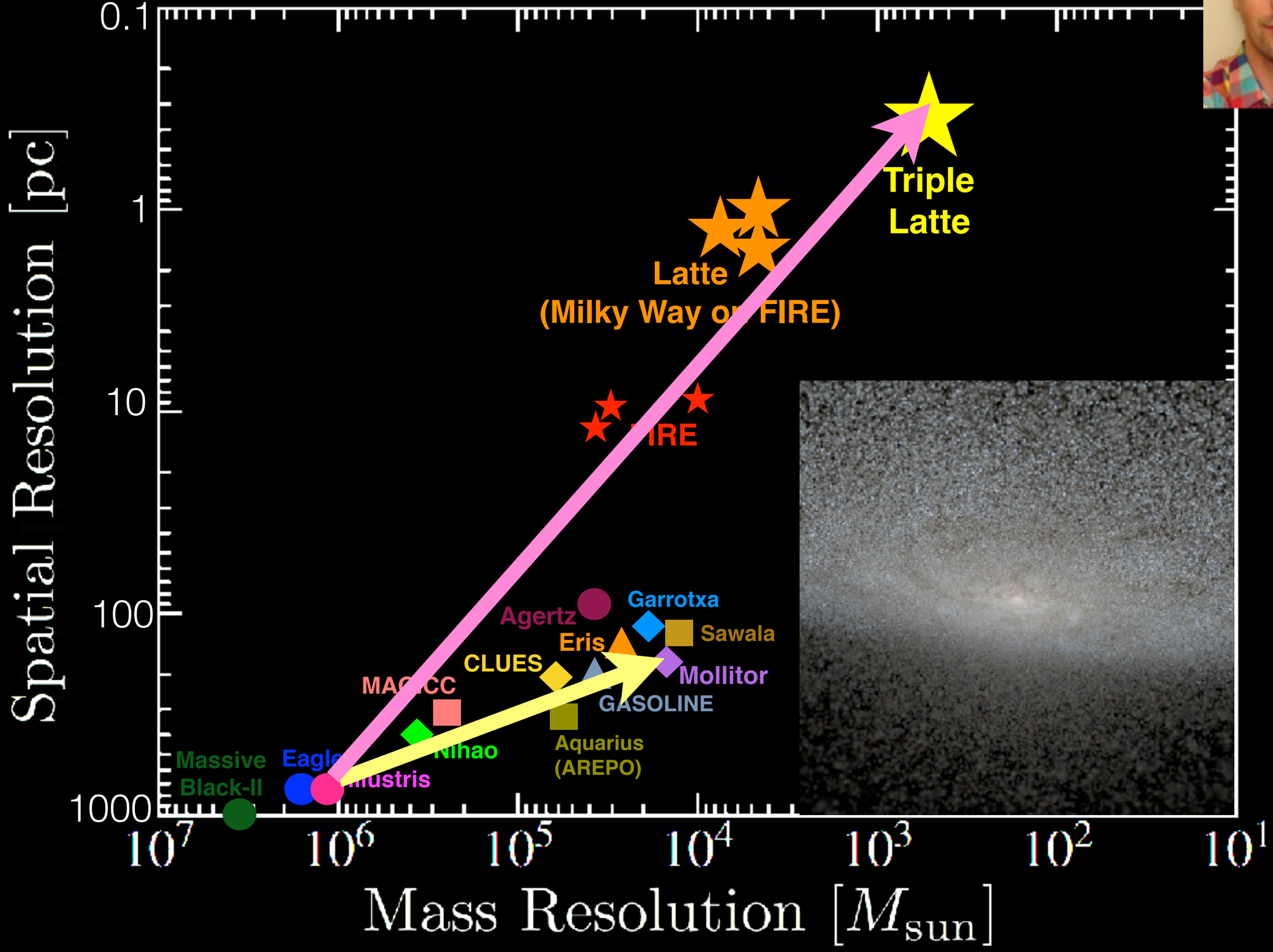
Red: hot $(> 10^6\,K)$

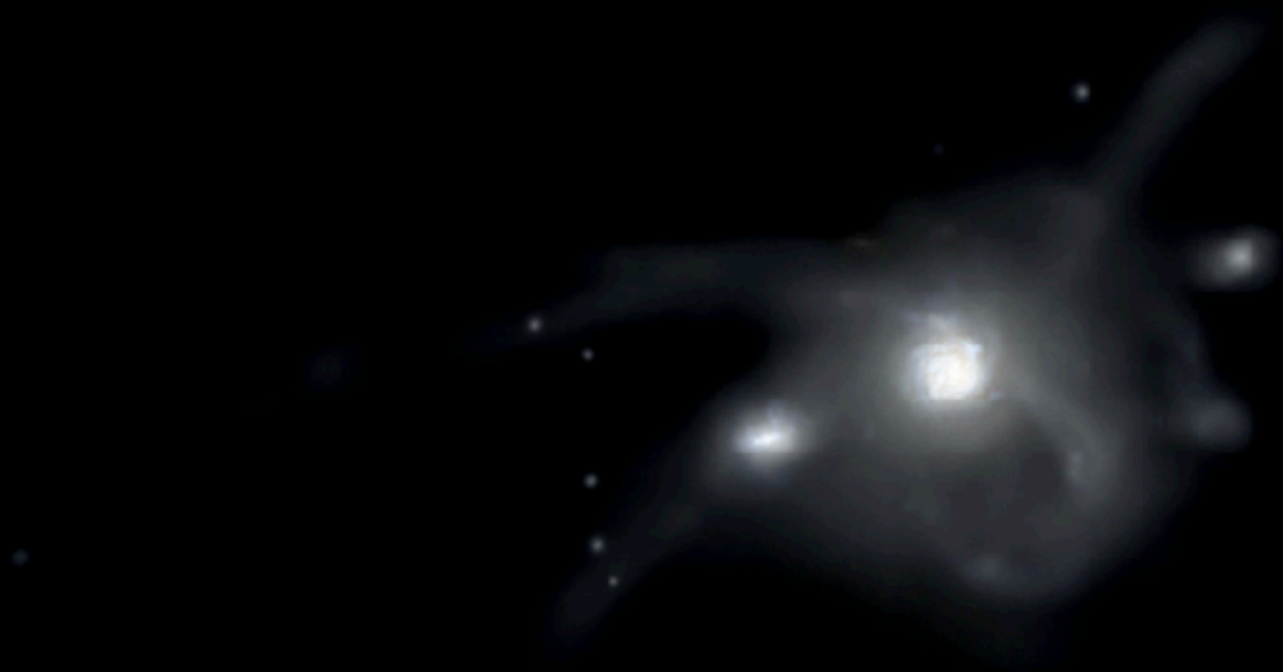
The Future is Now

ALGORITHMIC BREAKTHROUGHS ENABLE NEW PHYSICS

Andrew Wetzel (arXiv:1602.05957)



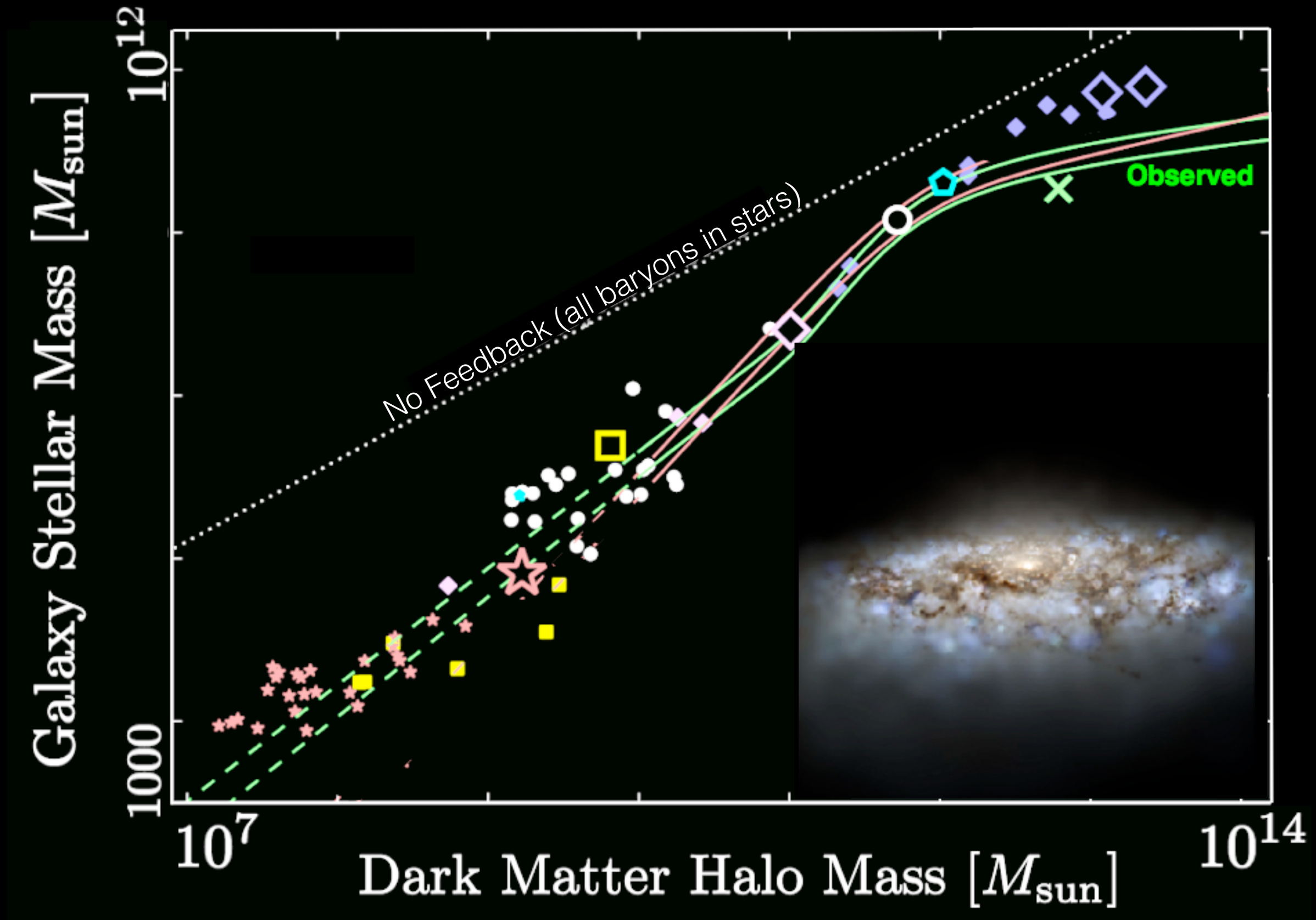




This Works (More or Less) if You Resolve Key Scales

GAS IS BLOWN OUT, INSTEAD OF TURNING INTO STARS

PFH et al.
(arXiv:1311.2073)



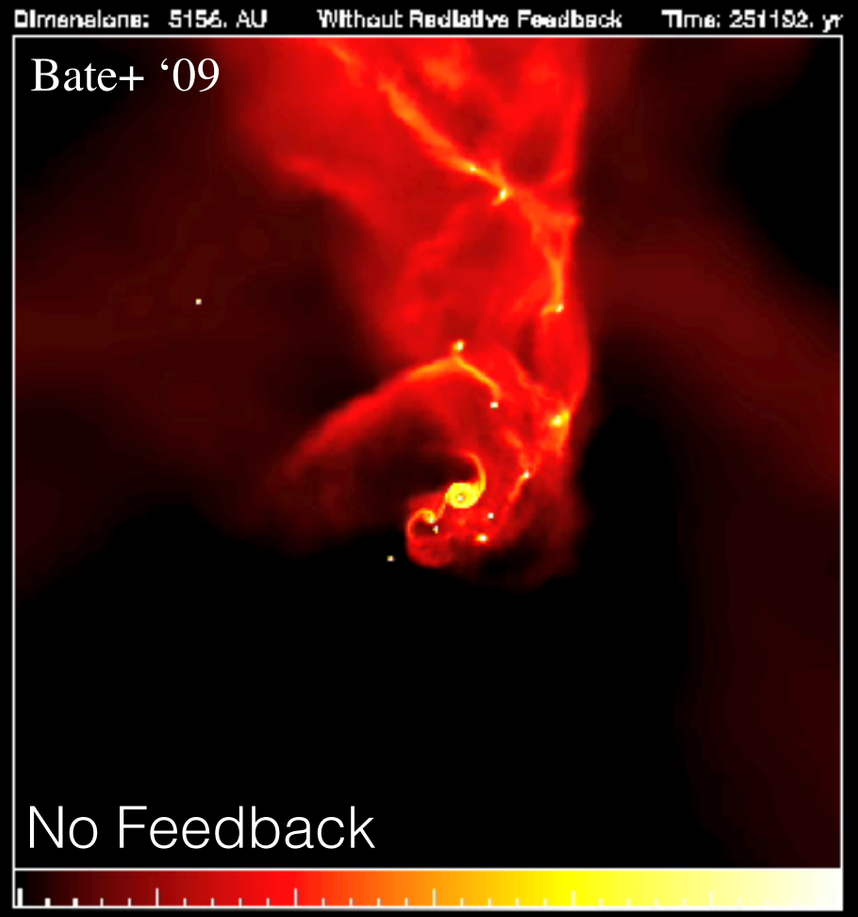
Feedback On All Scales
(From the Bottom-Up)

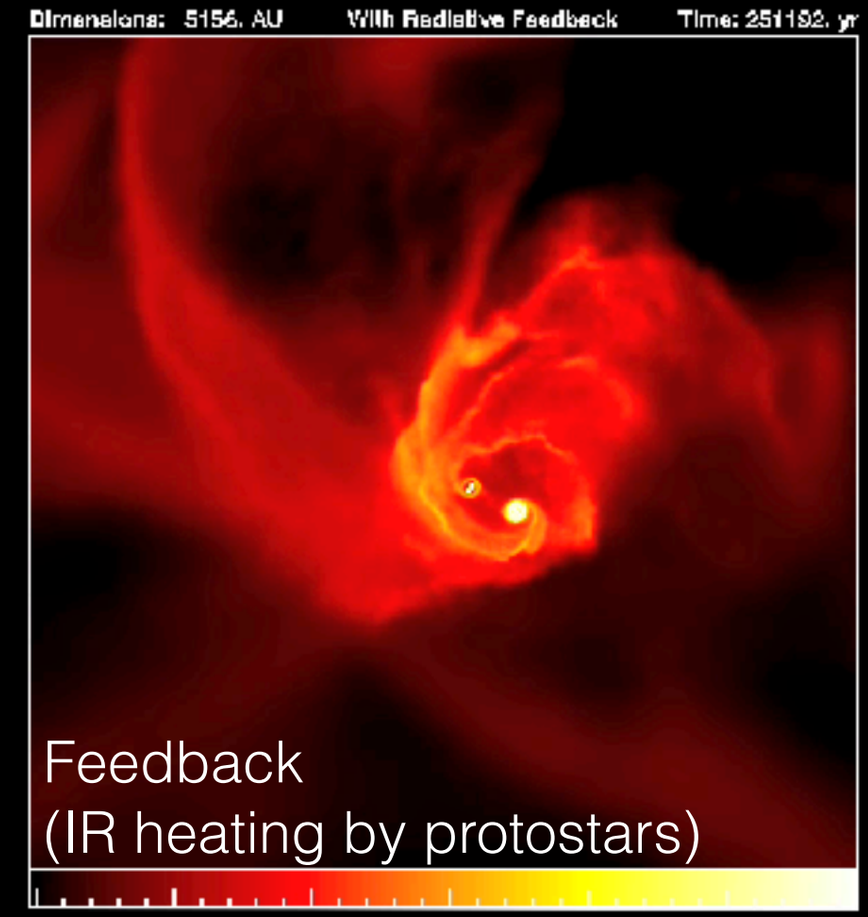
The IMF & Sub-Cloud Scales

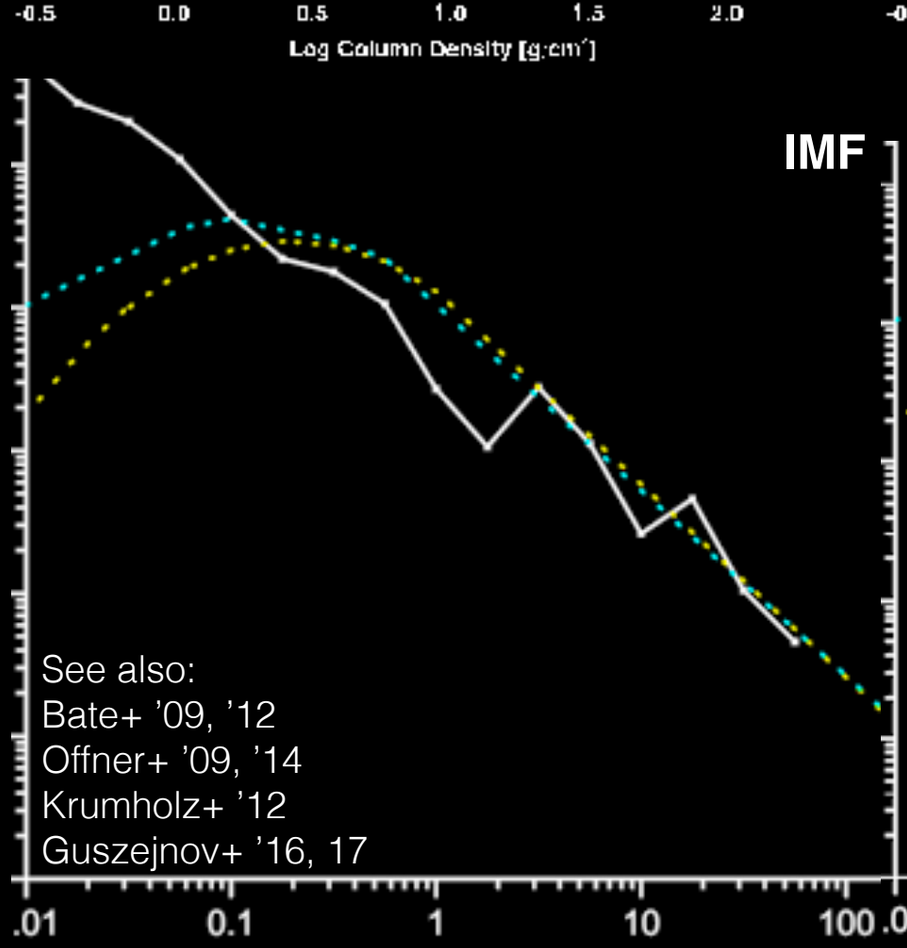
Feedback vs. Gravity

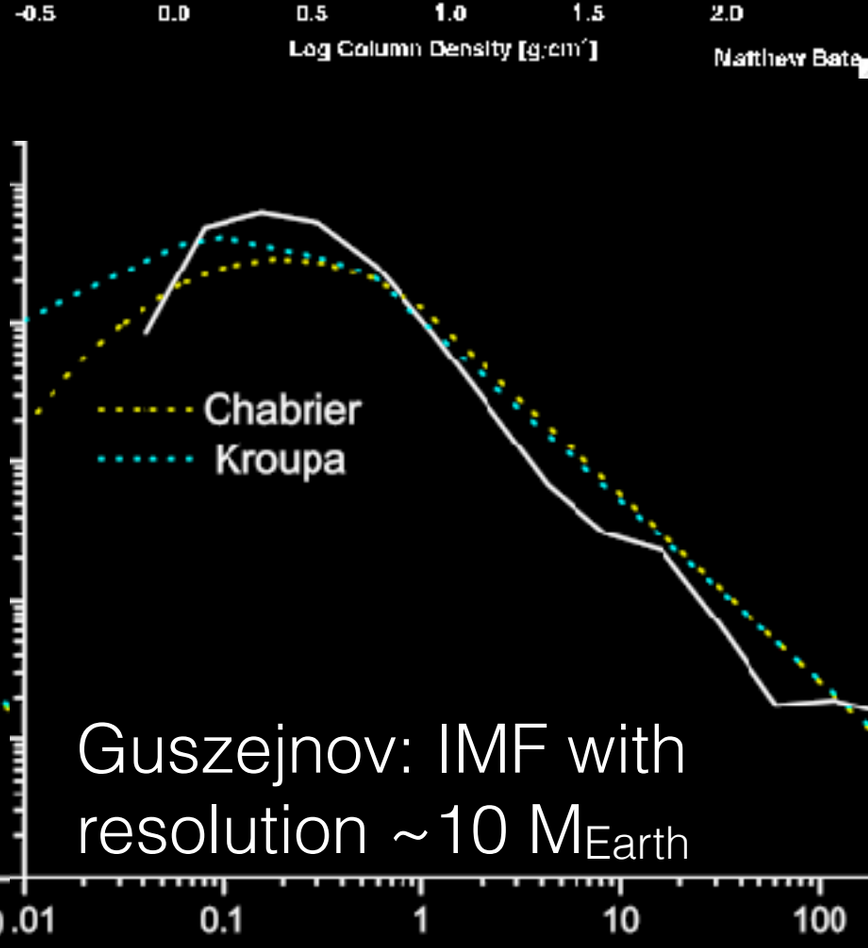
Guszejnov, Hopkins, & Krumholz
2015, 2016, 2017

EVERY VARIABLE-IMF MODEL USED EXTRA-GALACTICALLY IS WRONG (arXiv:1702.04431)



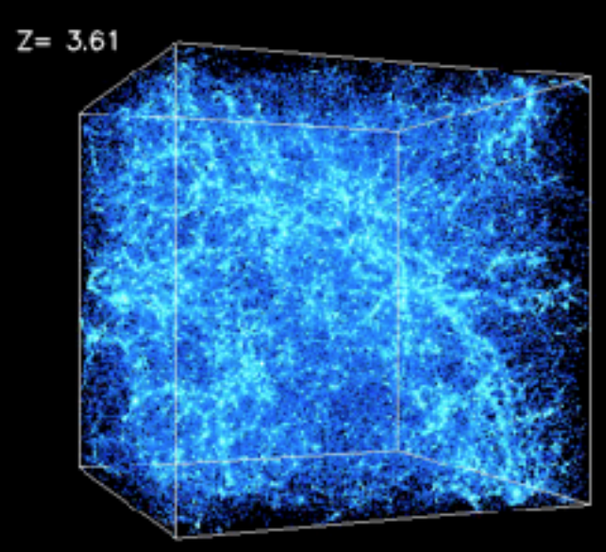




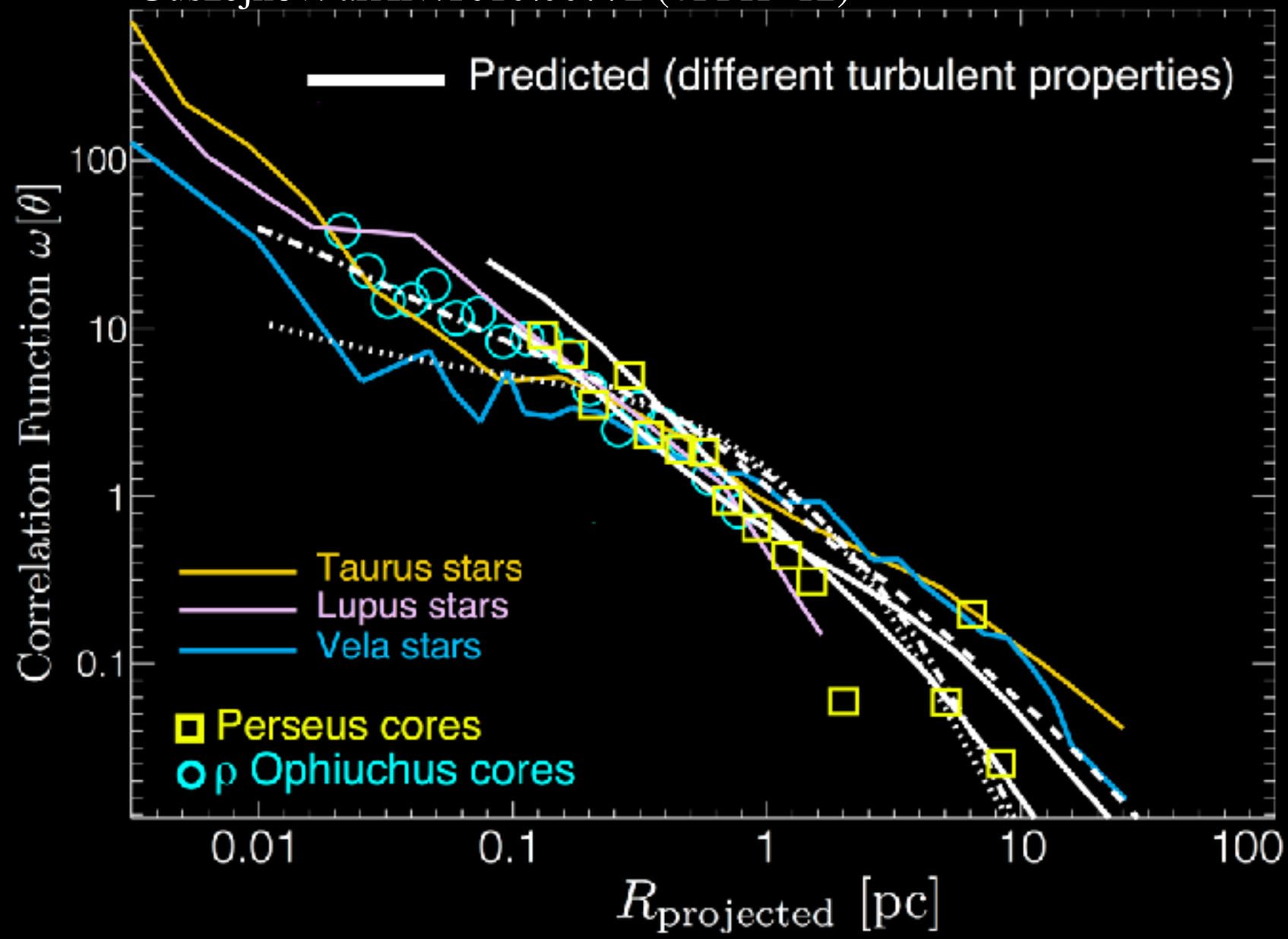


Why Is Star Formation Clustered?

INEVITABLE IN GRAVITATIONAL COLLAPSE



Guszejnov: arXiv:1610.00772 (+PFH '12)



Universal

(Guszejnov: 1707.05799):

Stars
Cores
Clumps
GMCs
Star clusters
Galaxies

$$\xi_{\rm 3d} \propto r^{-2}$$

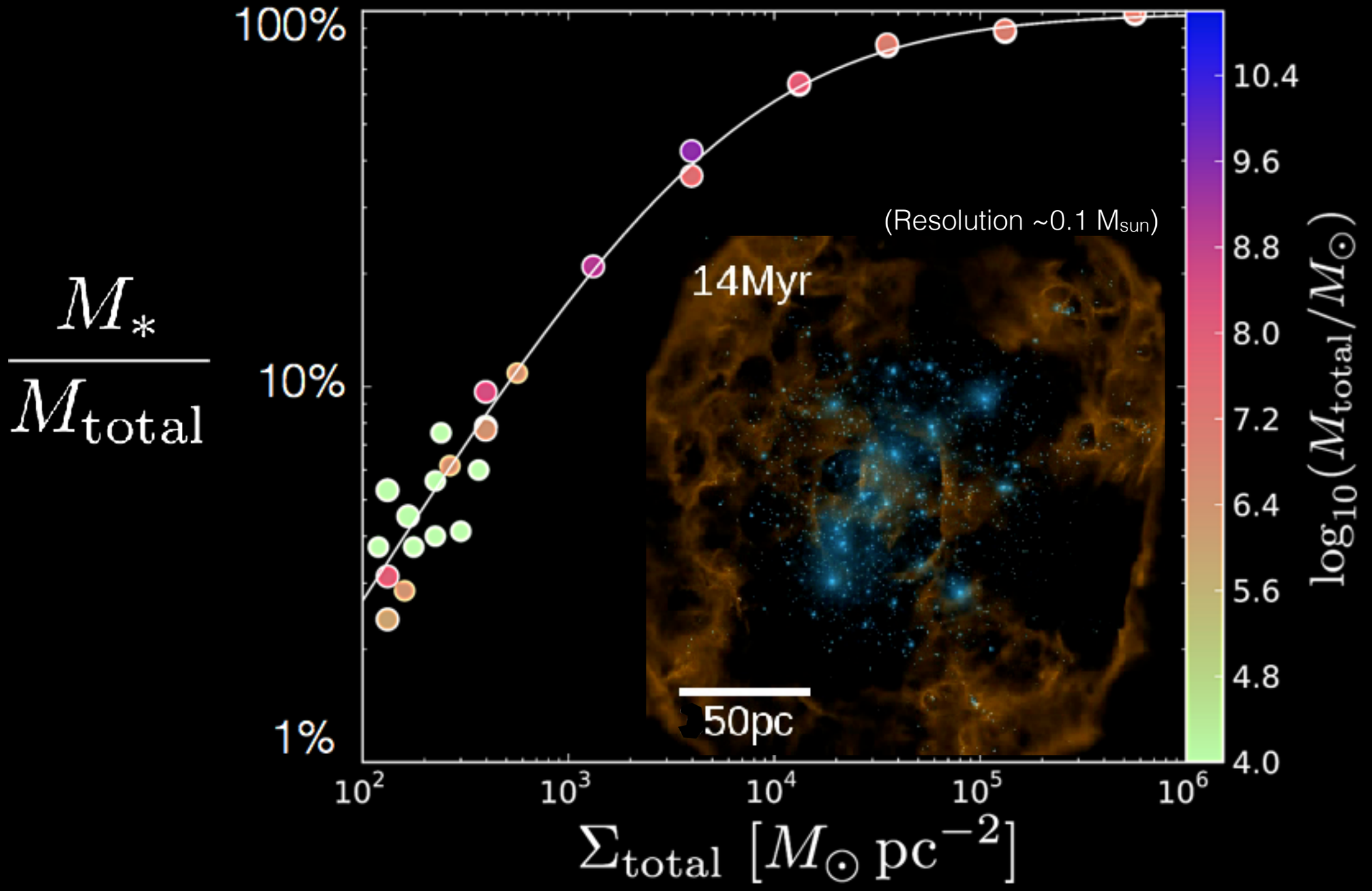
$$(\omega(\theta) \propto \theta^{-1})$$

GMC & Star Cluster Scales

What Determines Cloud Star Formation Efficiencies?

FEEDBACK VS. GRAVITY

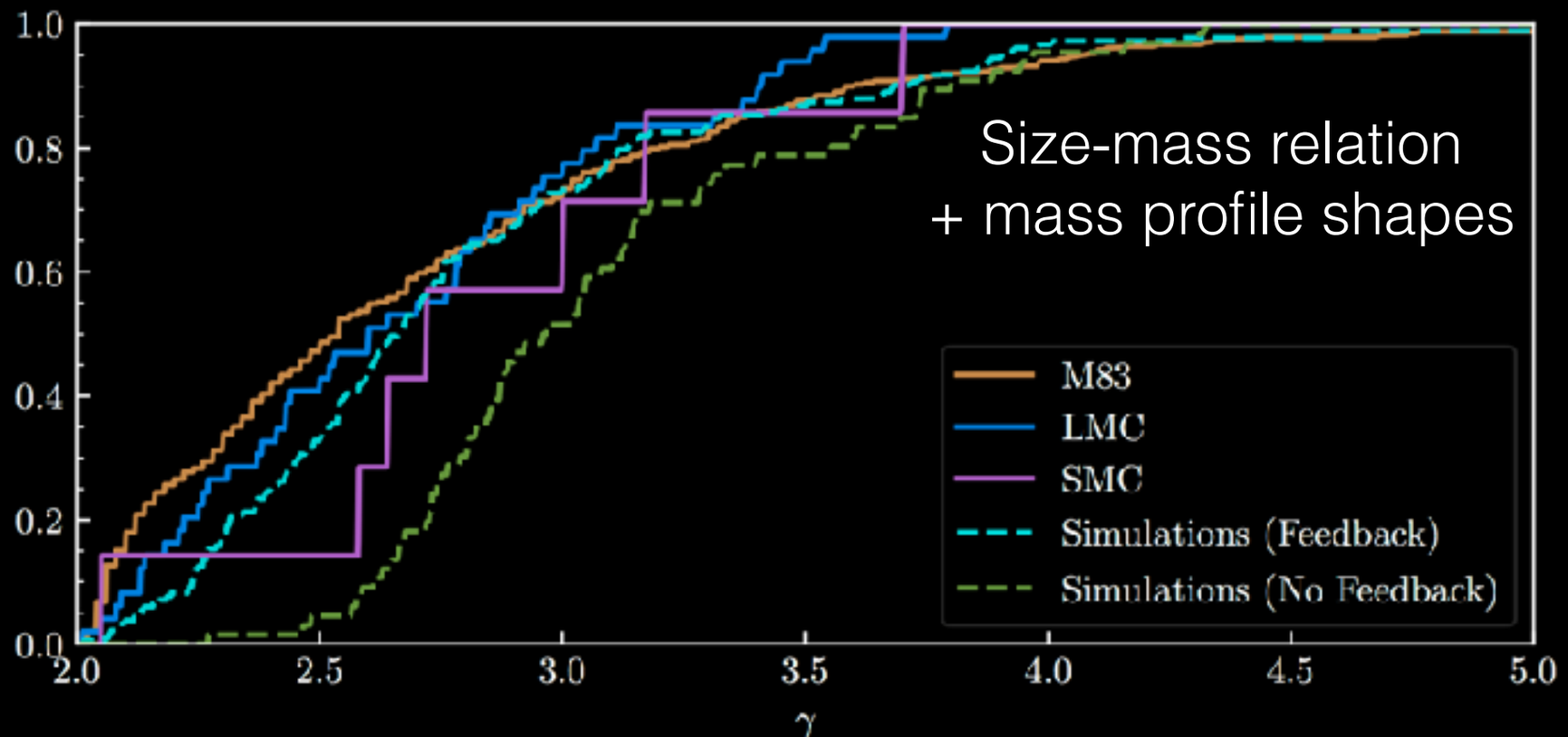
Mike Grudic
(arXiv:
1612.05635)



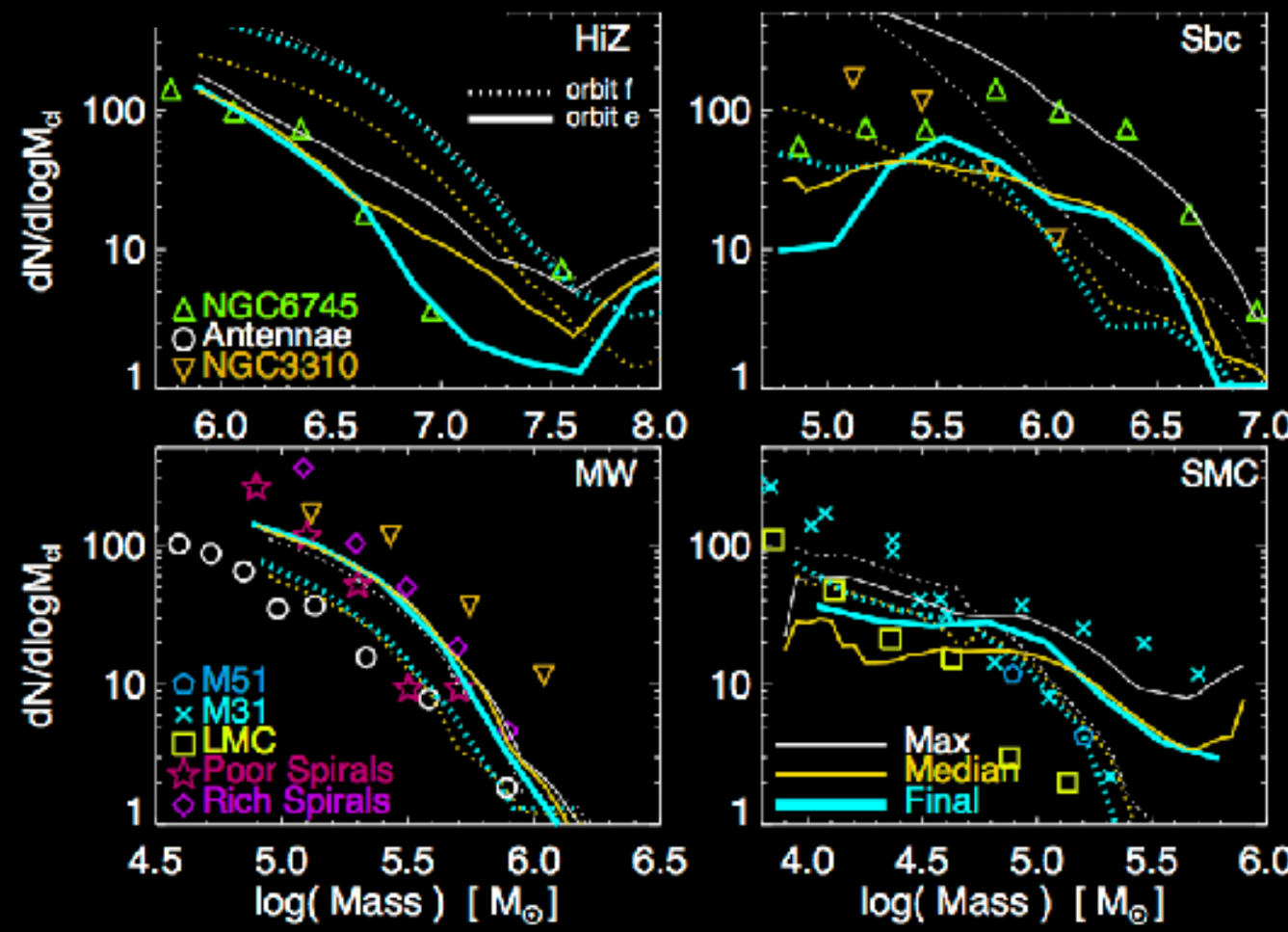
$$\text{Gravity} \sim \frac{G\,M_{\rm tot}\,M_{\rm gas}}{R^2} \propto M_{\rm tot}\,\Sigma_{\rm gas} \qquad \text{vs.} \qquad \text{Feedback} \sim \frac{\text{Momentum}}{\text{Time}} \propto (...)\,M_*$$

Mike Grudic
(in prep)

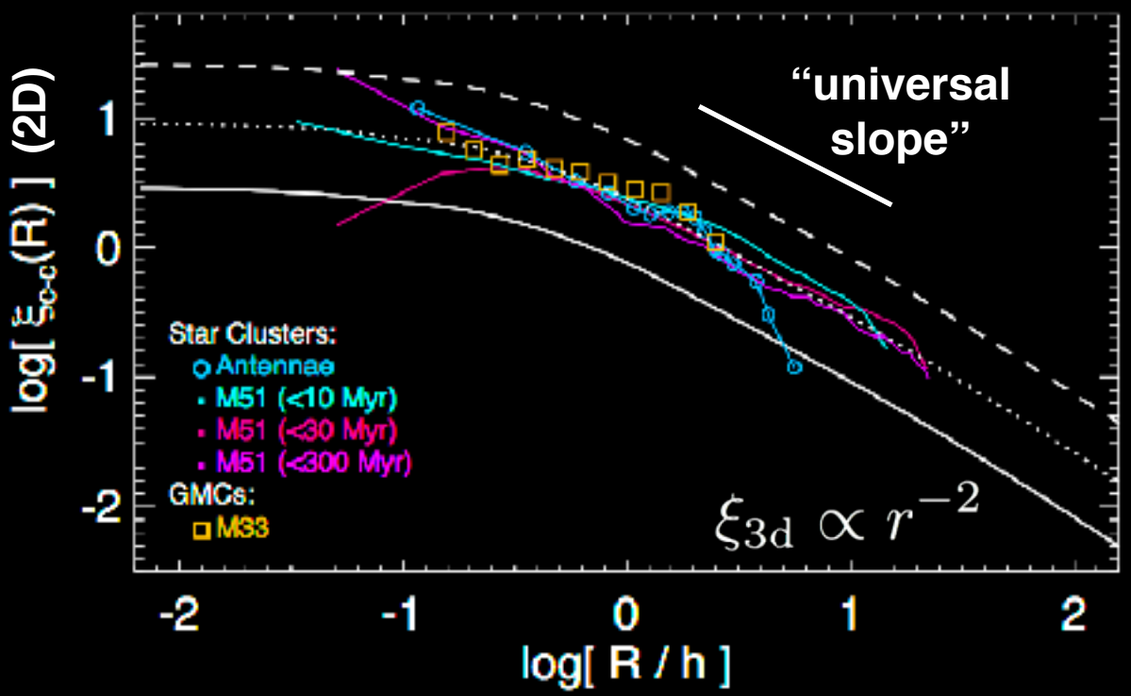
Size-mass relation + mass profile shapes



Mass functions (~M^{-2}) vs. environment



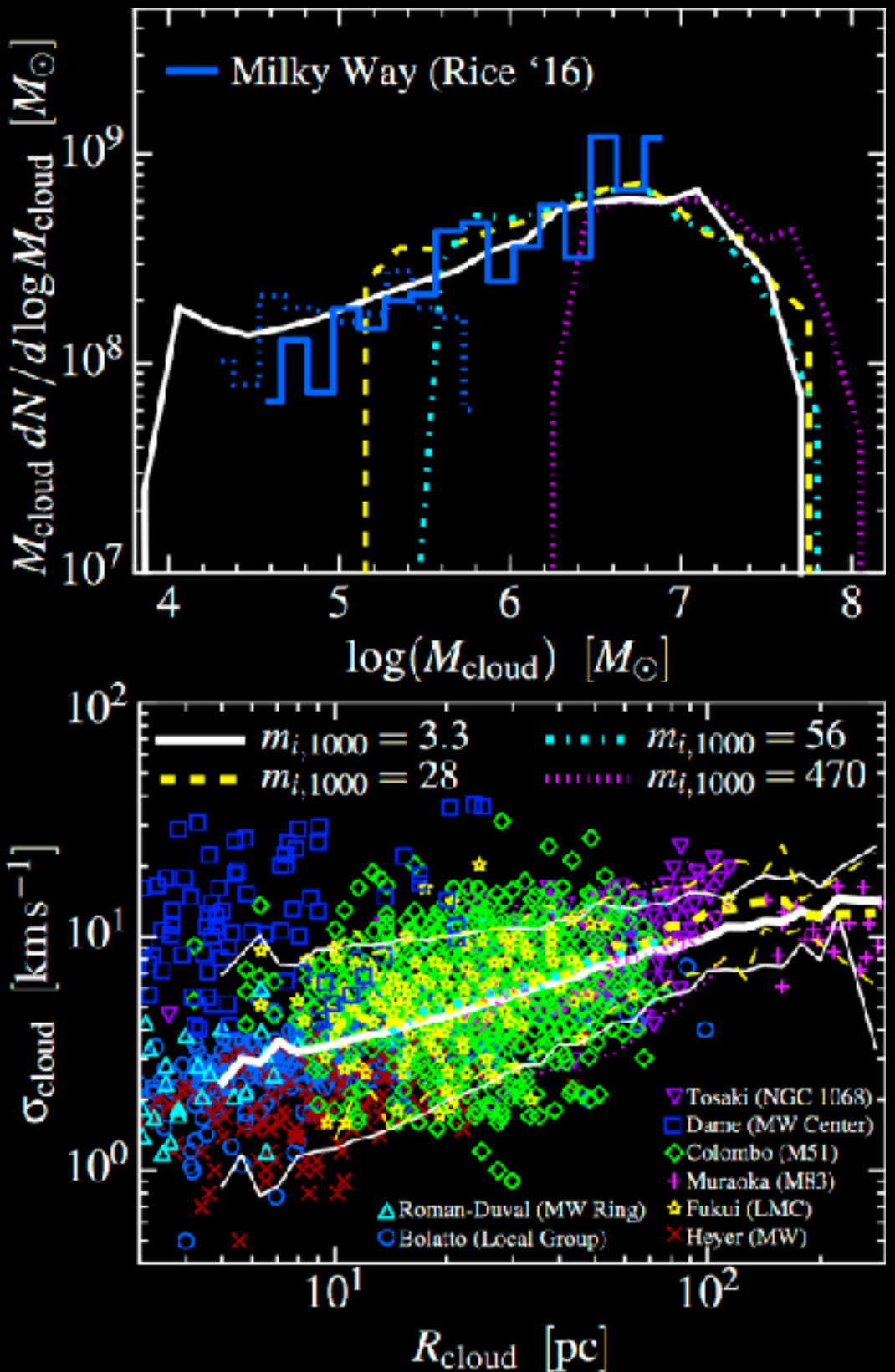
Correlation functions



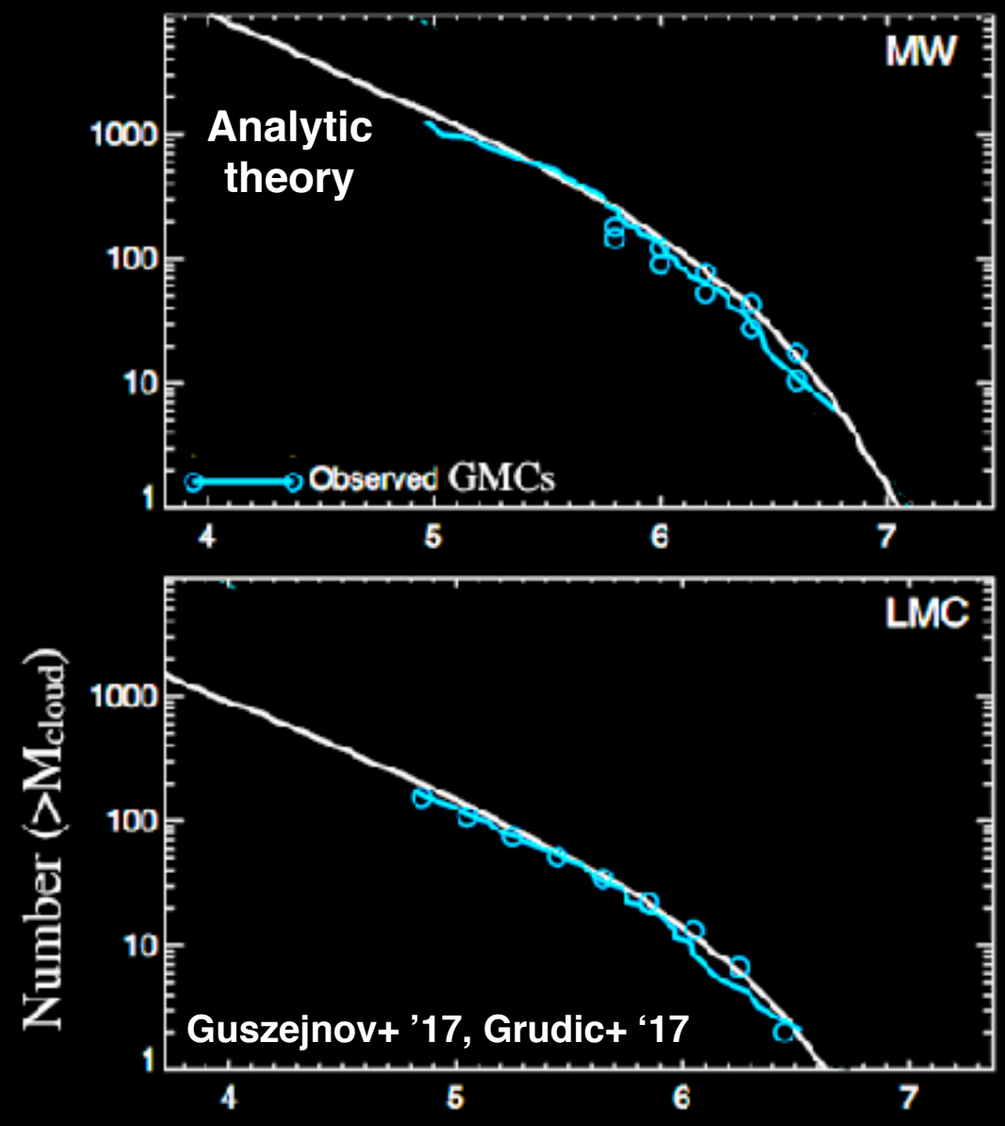
GMCs: Turbulence+Gravity+Feedback

RESOLVING "TOP SCALE" OF FRAGMENTATION

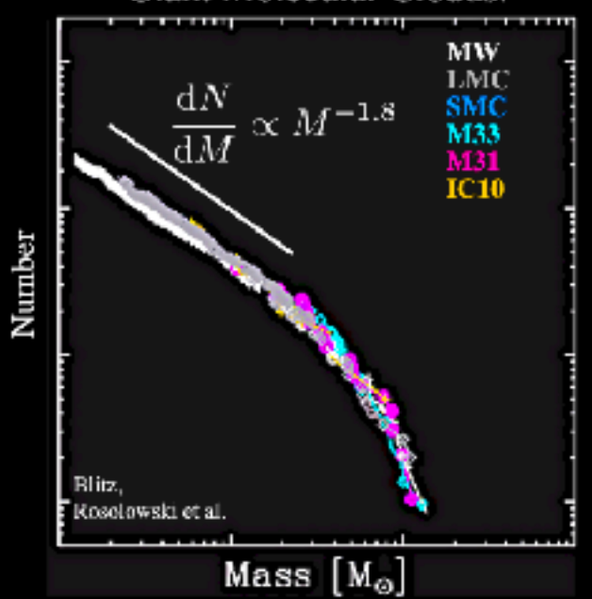
FIRE simulations: Guszejnov (arXiv:1702.04431)

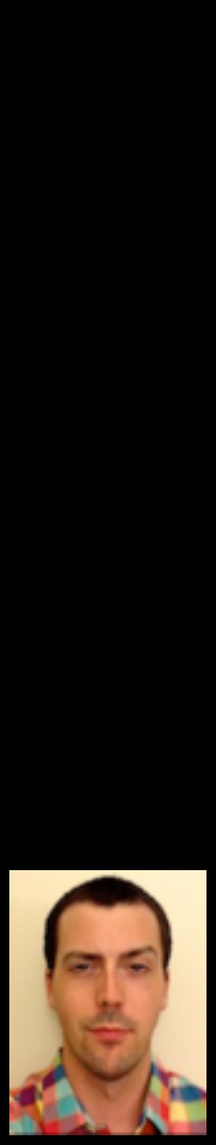


(+cloud lifetimes, SF efficiencies, virial parameters)



"Universal" Mass Function (GMCs, star clusters, and more!)



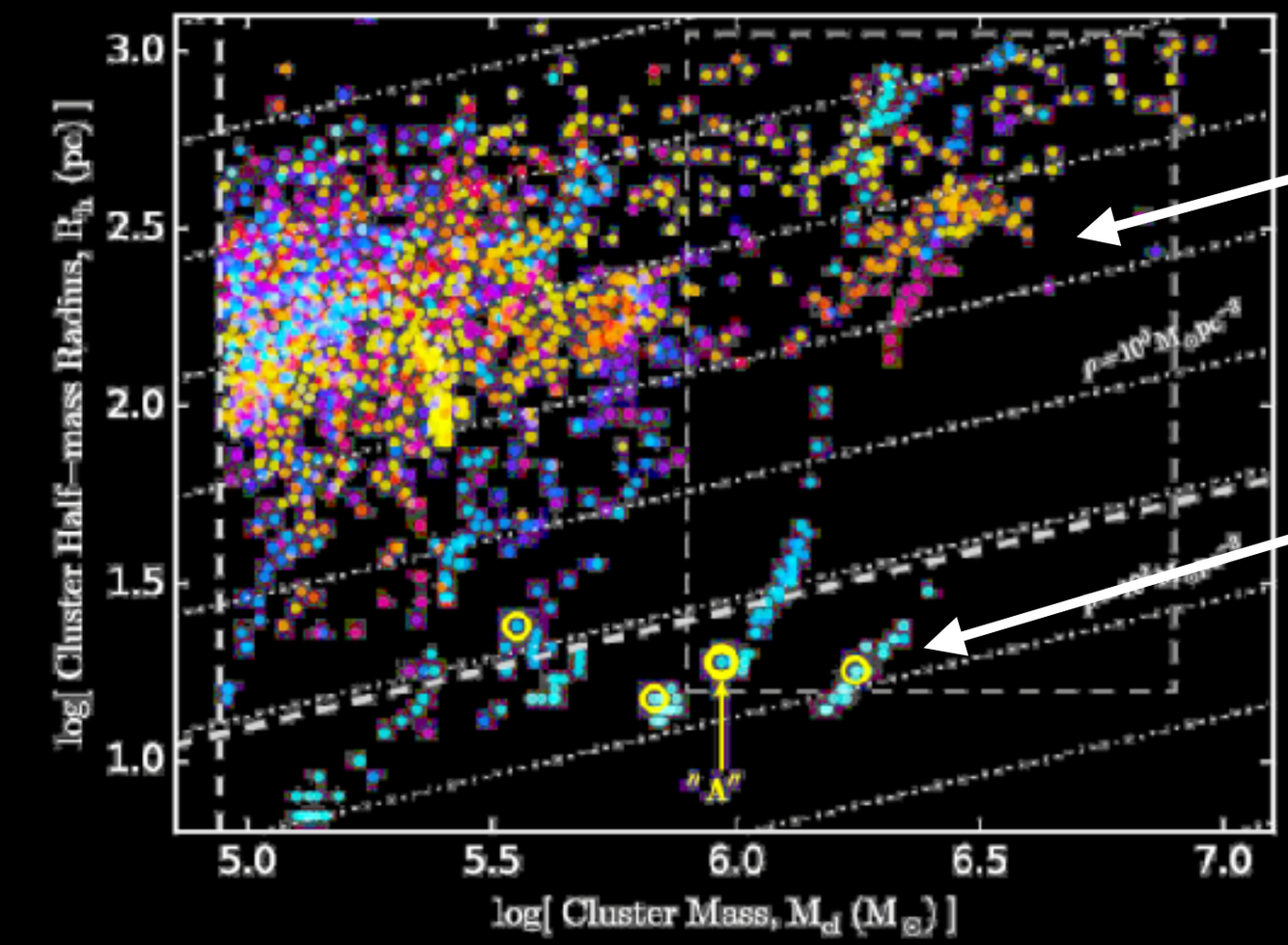


Andrew Wetzel
(arXiv:1602.05957)

“Triple Latte” (A. Wetzel): Cosmological MW with ~800 M_{sun} , sub-pc resolution

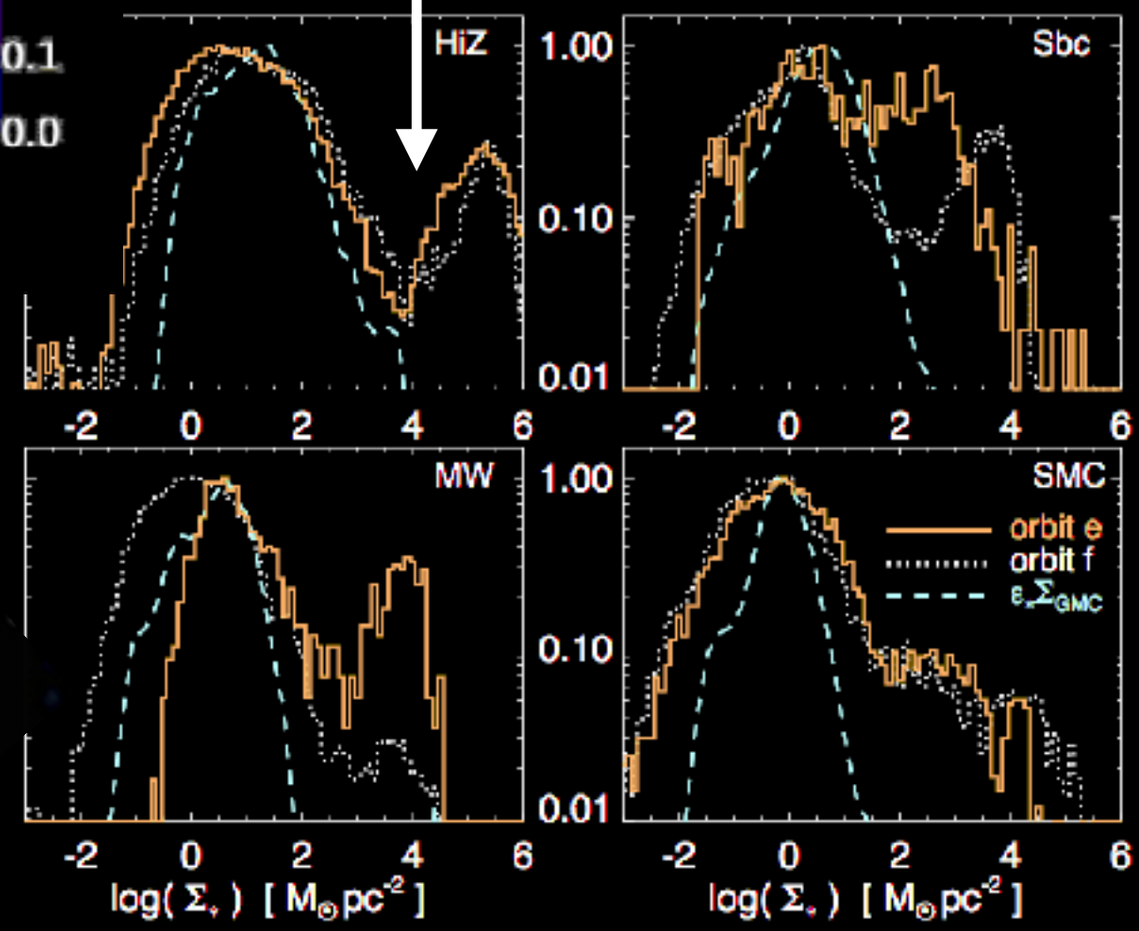
Resolving Globulars in Cosmological Simulations

(KIM '17 + GRUDIC '17)



Most form open clusters

Except long-lived population, around critical Σ_{cloud}



Ji-Hoon Kim (arXiv: 1704.02988)

~kpc Scales: Kennicutt-Schmidt

KS Law Emerges Naturally

FEEDBACK VS. GRAVITY

Matt Orr (1701.01788)
Agertz+14 , PFH+ 11,12,14
Shetty & Ostriker ’08.11, Kim & Ostriker ’11,13

No Feedback

Observed

$$\frac{\text{Feedback}}{\text{Area}} \propto (...)\,\dot{\Sigma}_*$$

$$\frac{\text{Gravity}}{\text{Area}} \propto G\,\Sigma_{\rm tot}\,\Sigma_{\rm gas} \propto \Sigma_{\rm gas}^{1-2}$$

$\log(\,\Sigma_{\rm SFR}\,)$ $[\mathrm{M_\odot\ yr^{-1}\ kpc^{-2}}]$

$\log(\,\Sigma_{\rm gas}\,)$ $[\mathrm{M_\odot\ pc^{-2}}]$

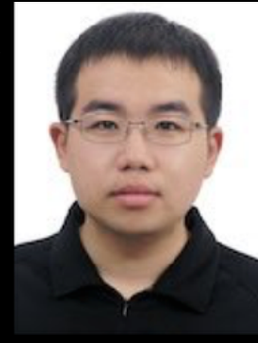
2 1 0 −1 −2 −3 −4 −5

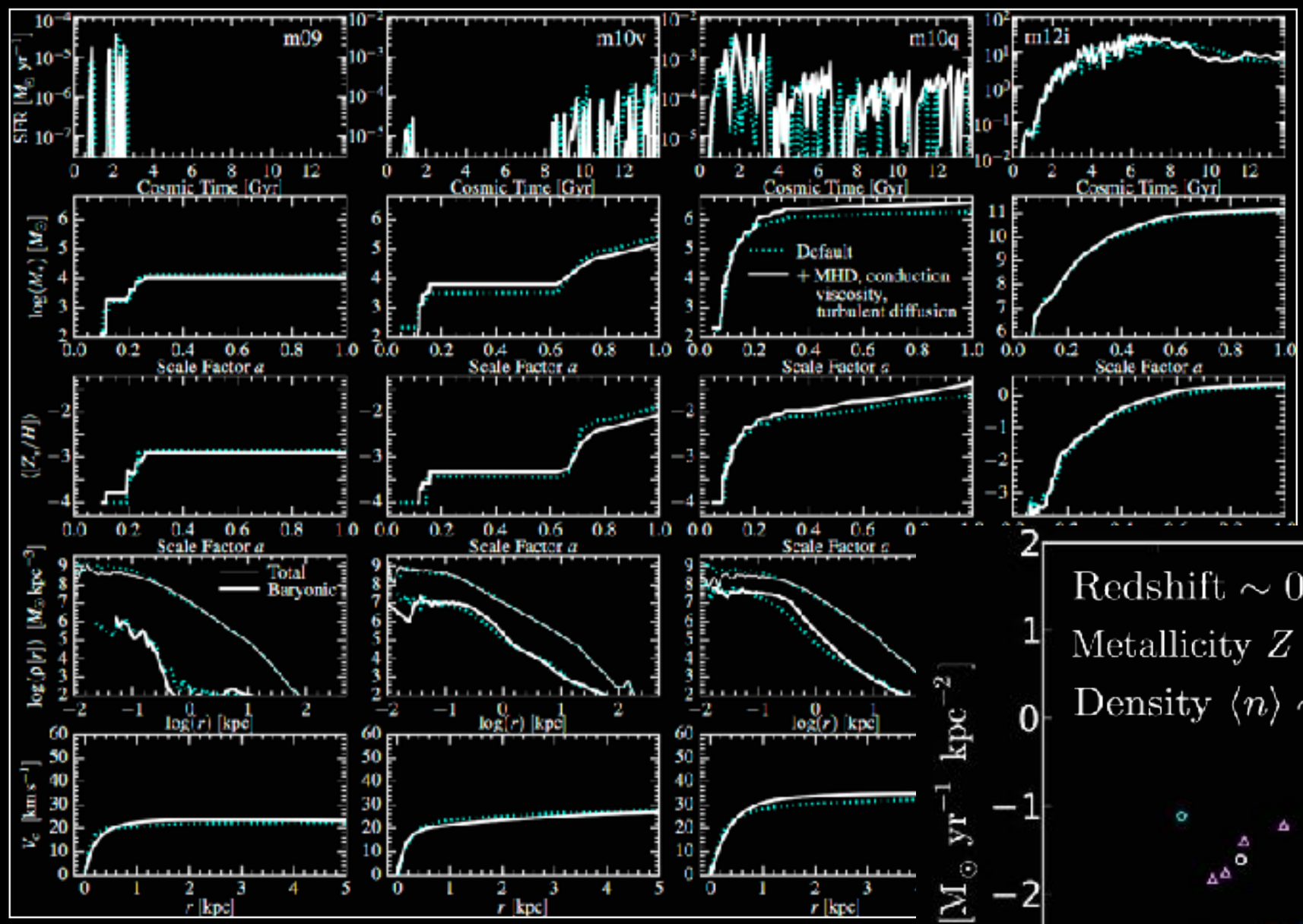
0 1 2 3 4

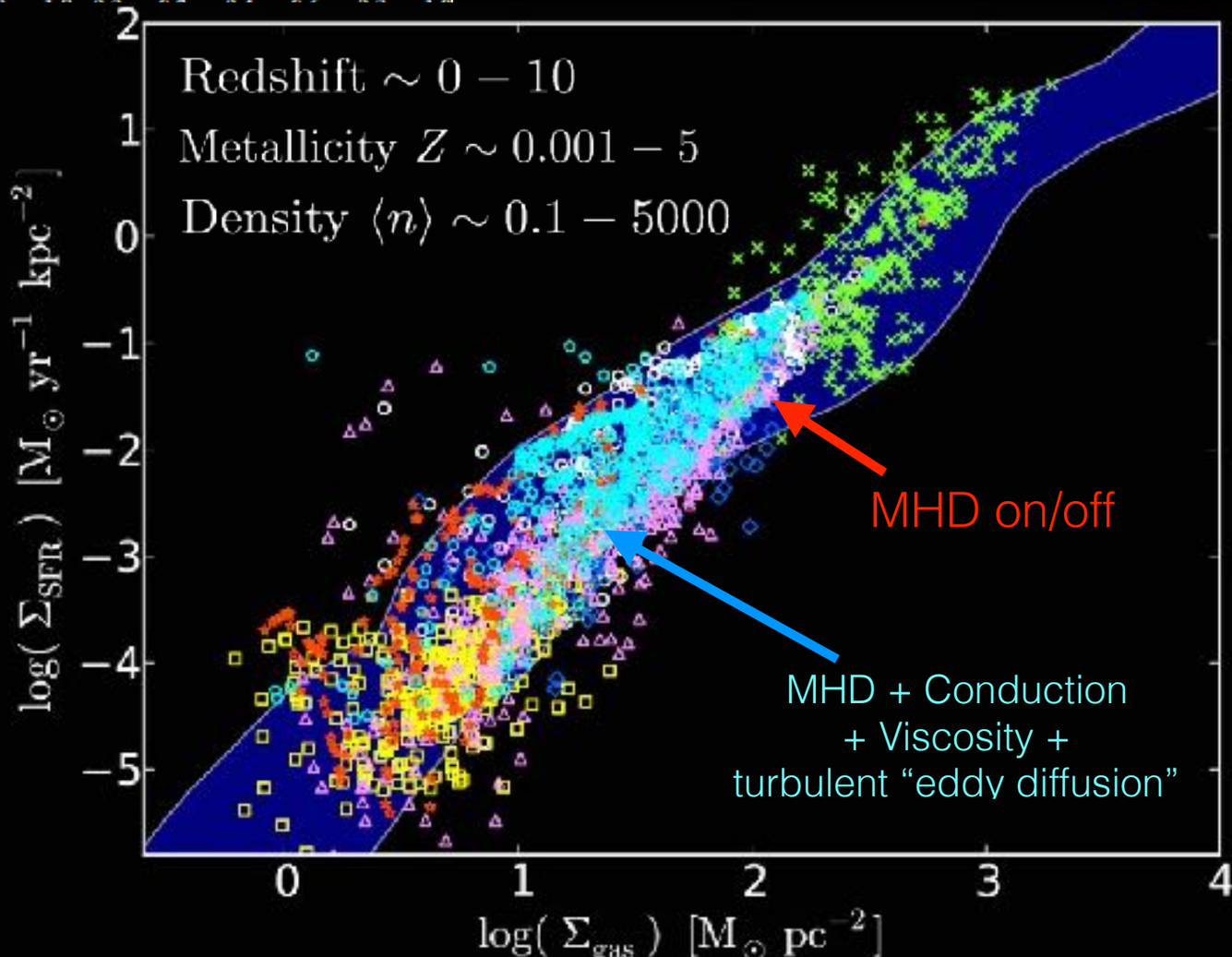
No dependence on MHD, conduction, viscosity, etc.

ONLY SEE IF FEEDBACK IS ARTIFICIALLY WEAK

Kung-Yi Su
(arXiv:
1607.05274)



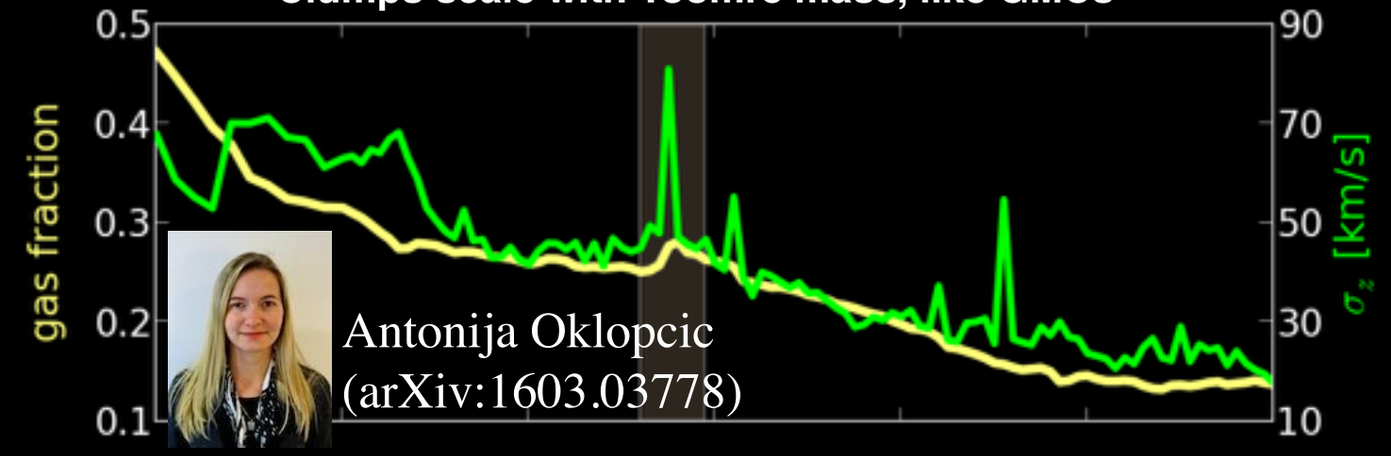




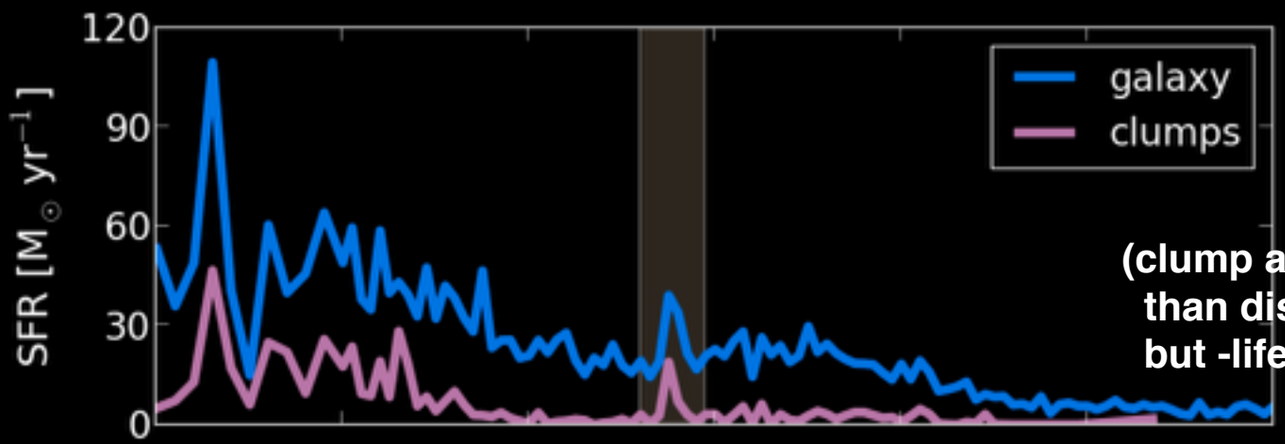
Giant "Clumps"

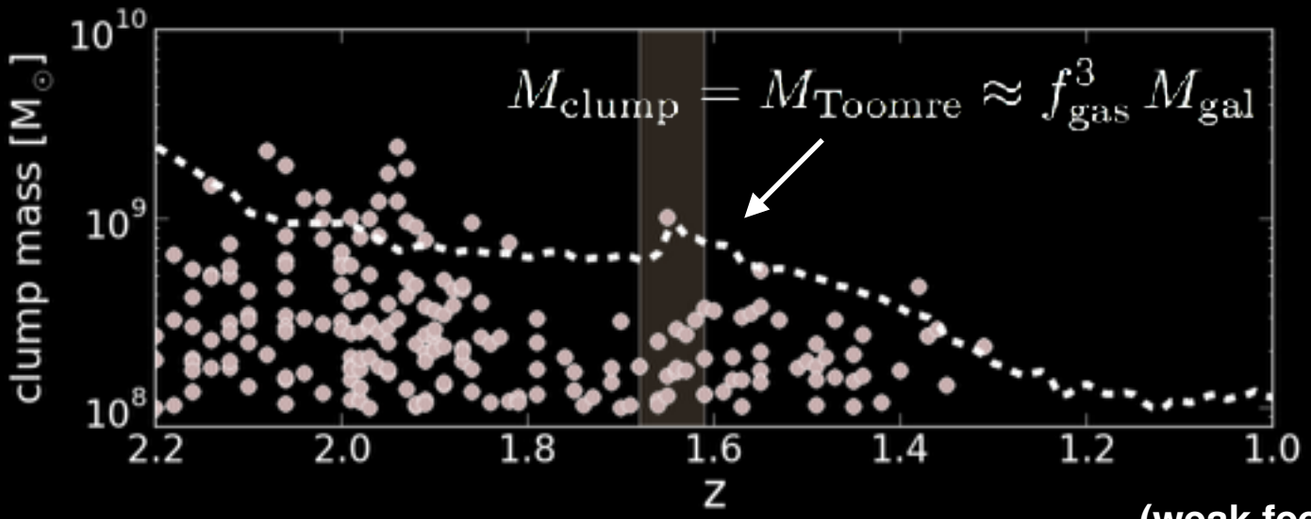
JUST AN EXTENSION OF GMCs

Clumps scale with Toomre mass, like GMCs



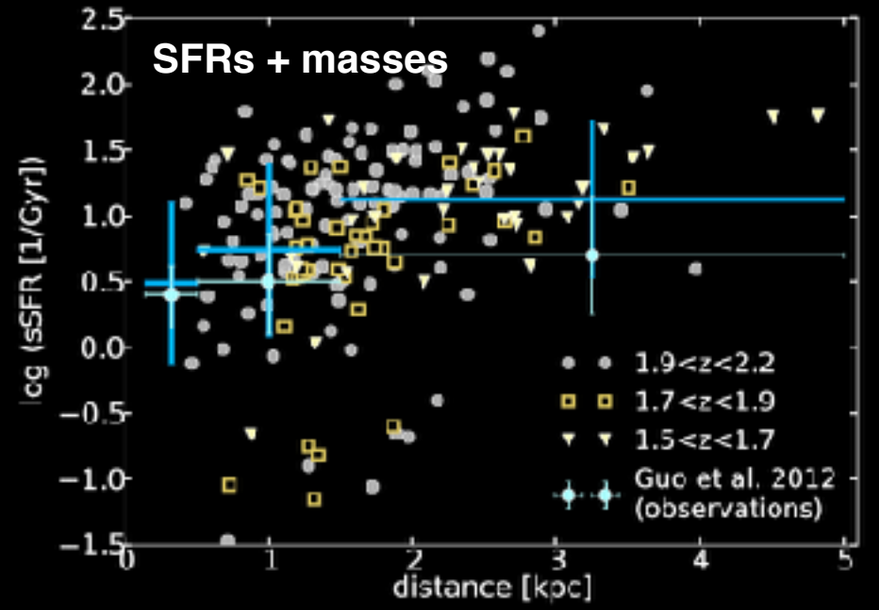
Antonija Oklopcic
(arXiv:1603.03778)

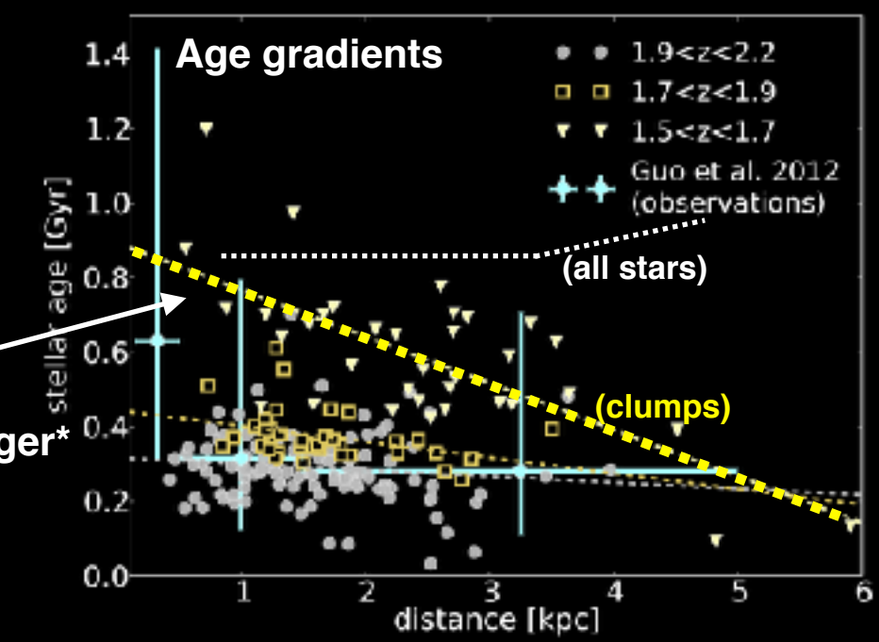




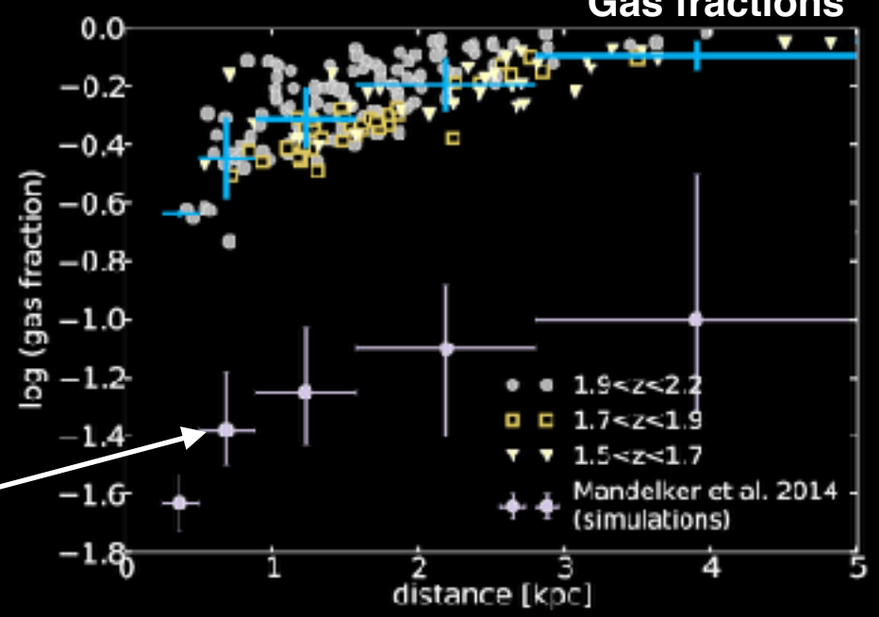
(clump age gradients *stronger* than disk, "ages" >1 Gyr, but -lifetimes- short)

(weak feedback, long-lived clump model)



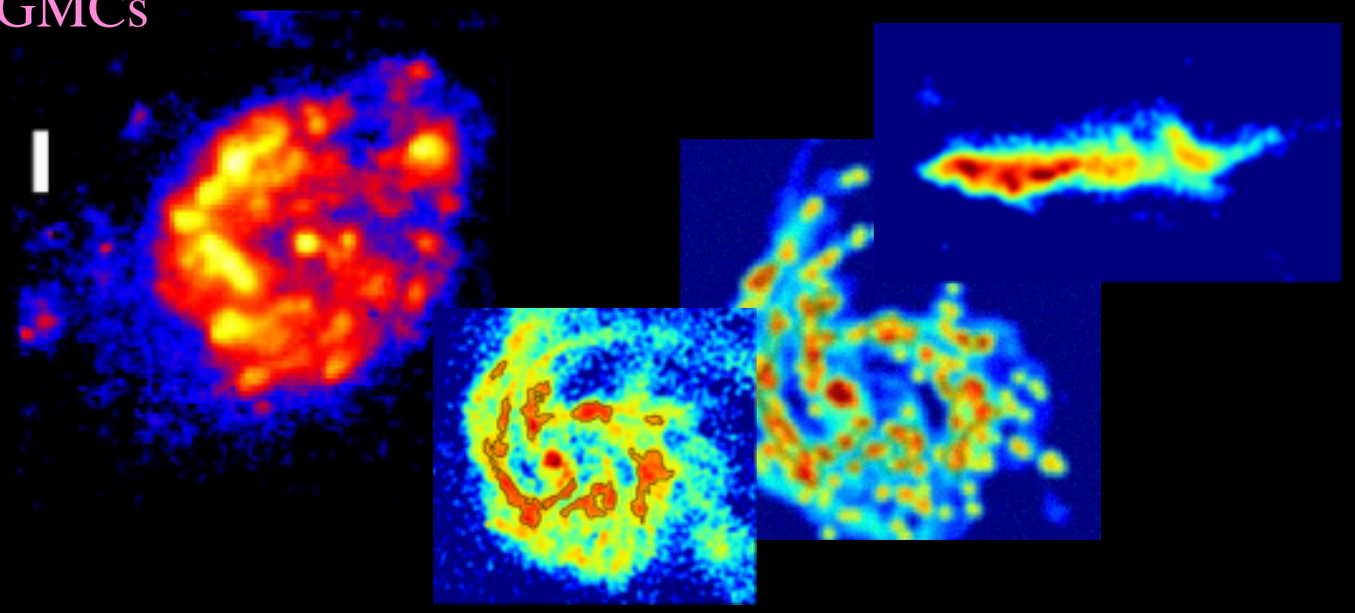


Gas fractions

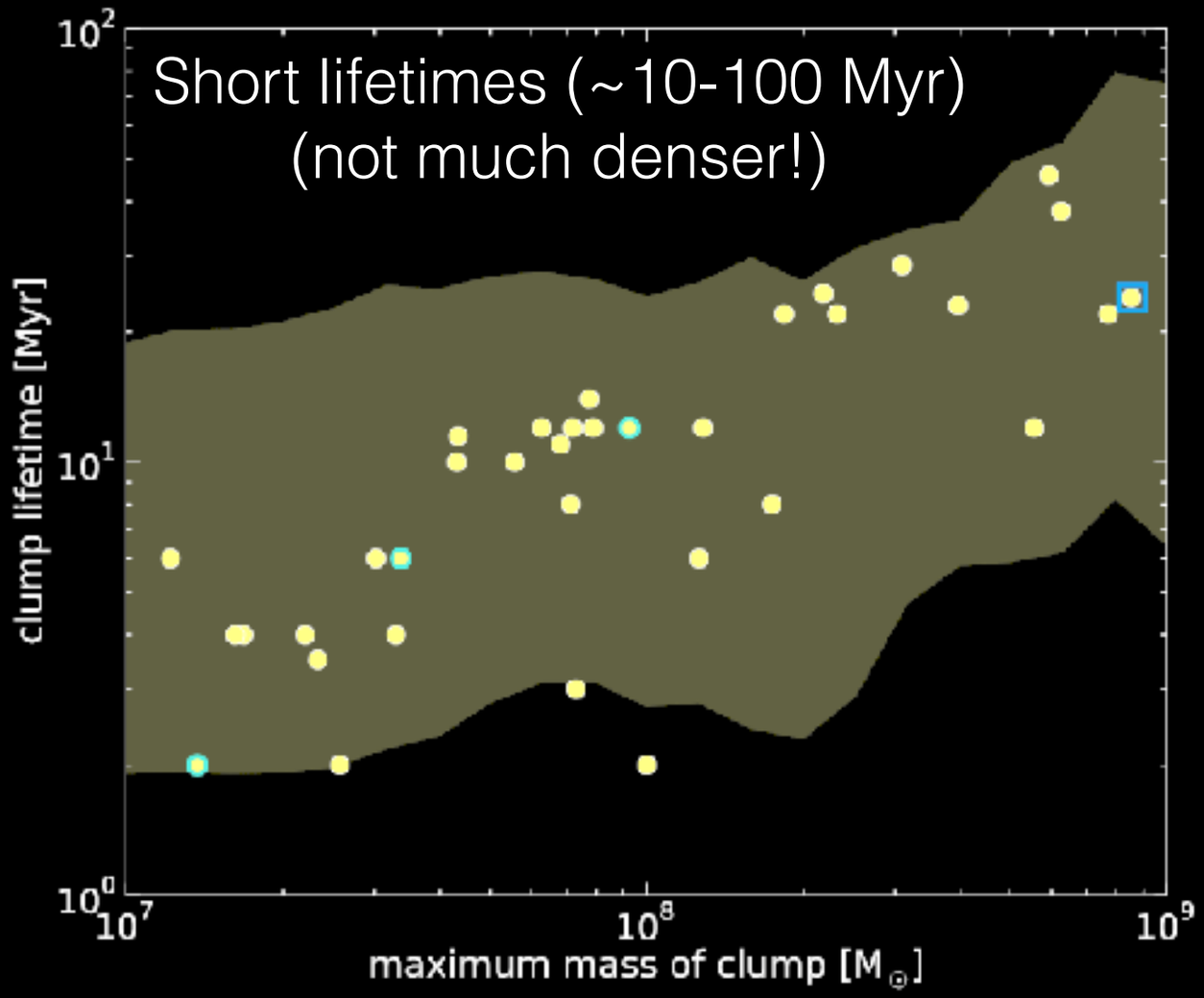


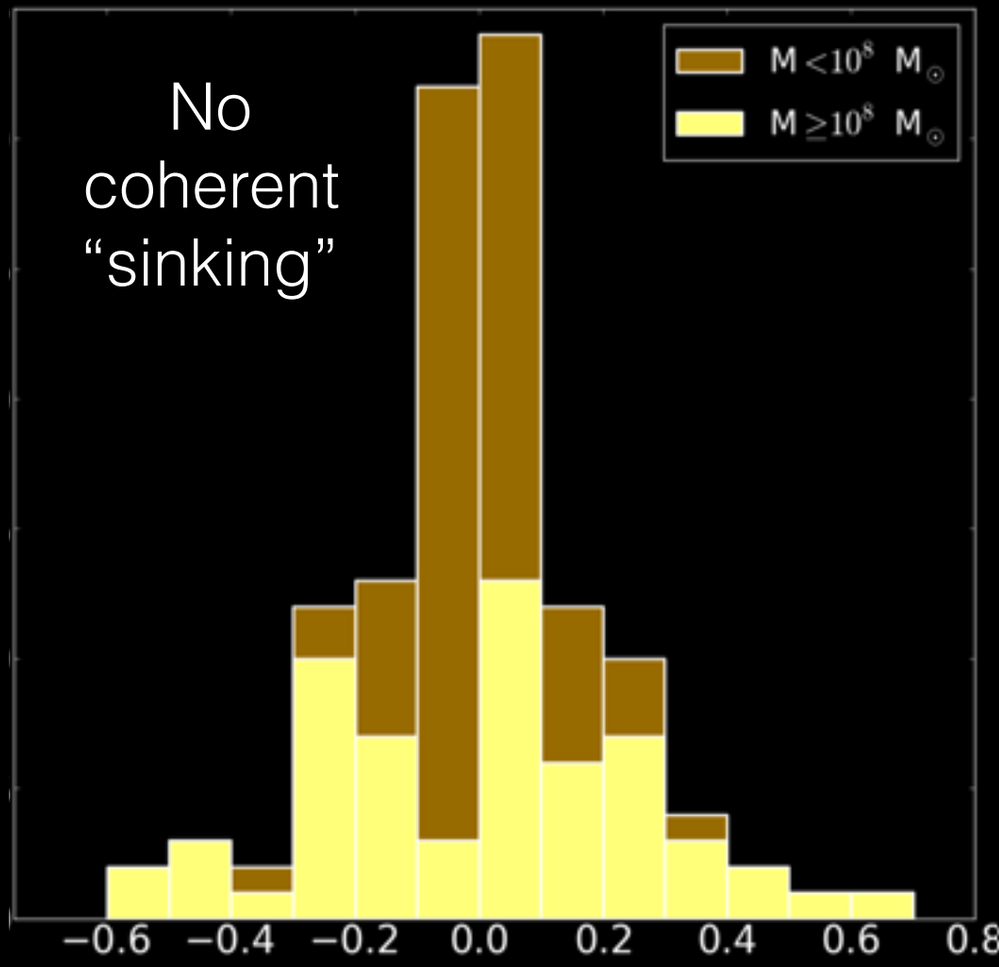
Giant "Clumps" Blow Up, Don't Sink

JUST AN EXTENSION OF GMCs



Antonija Oklopcic
(arXiv:1603.03778)





Fractional Change in Clump Orbital Angular Momentum

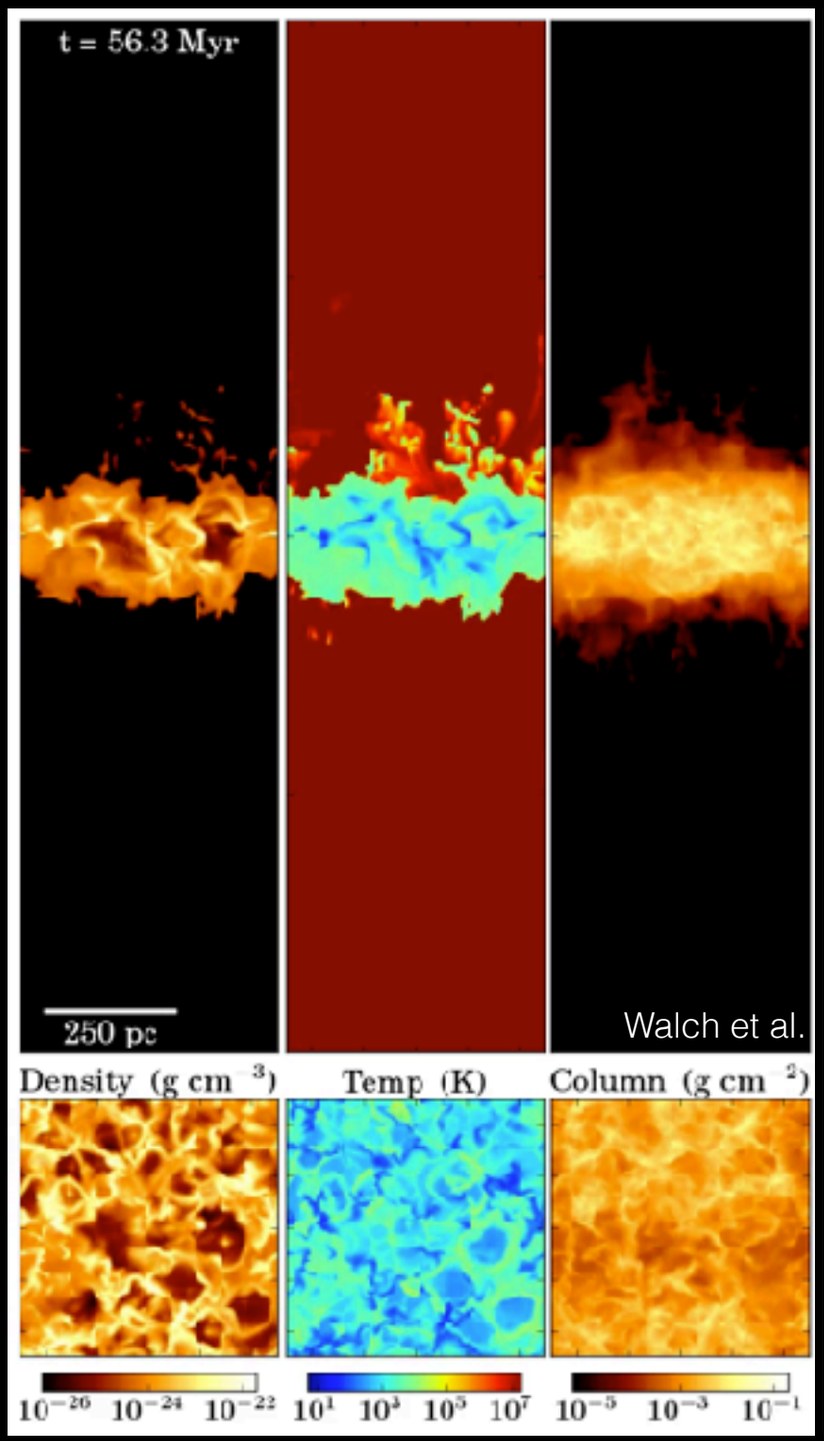
Galactic/Cosmological SFRs:
Driving Winds

Remember Stellar Clustering?

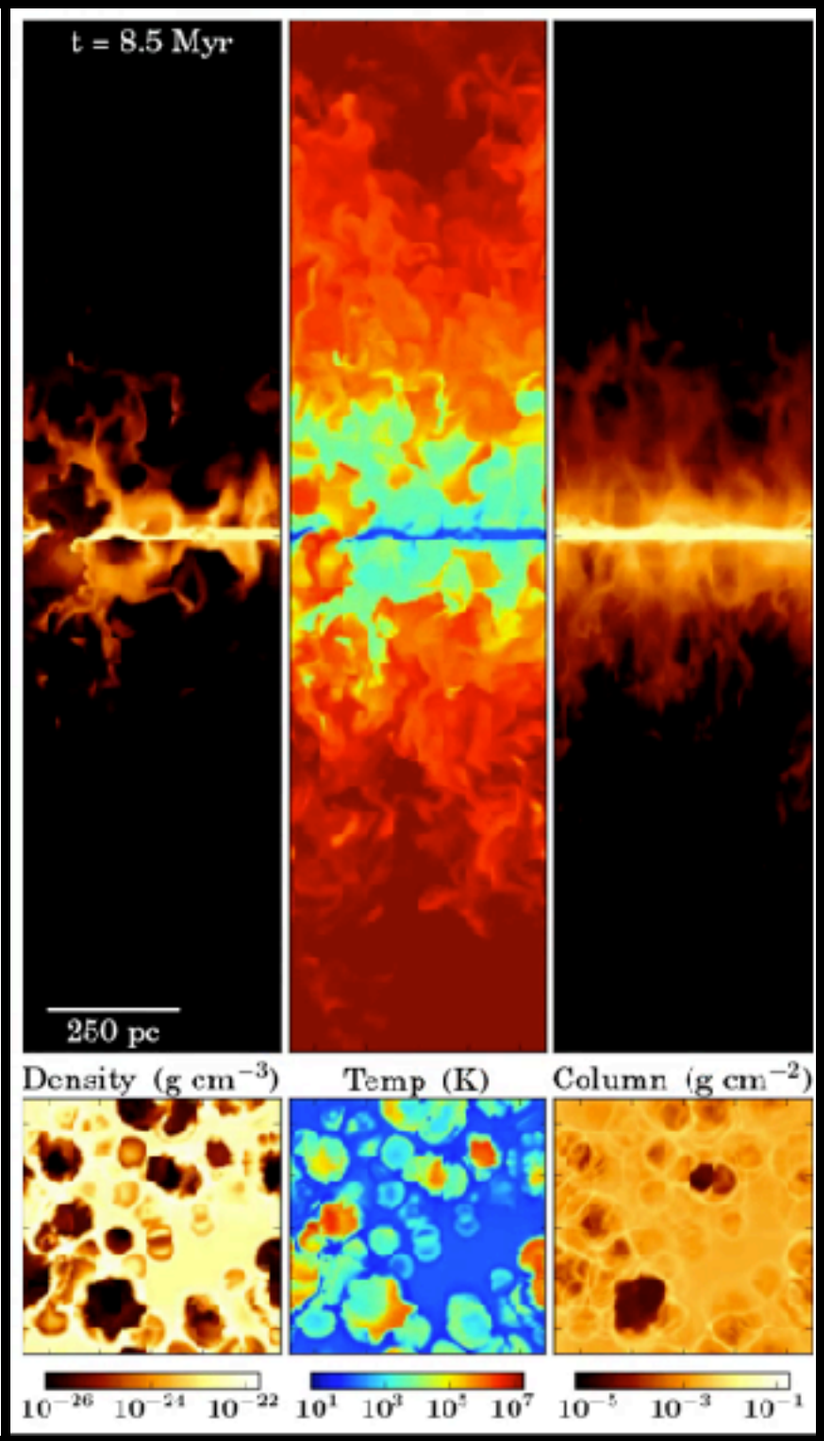
THIS MATTERS, A LOT!

Martizzi+ ’16
Walch+, Kimm+,
many others

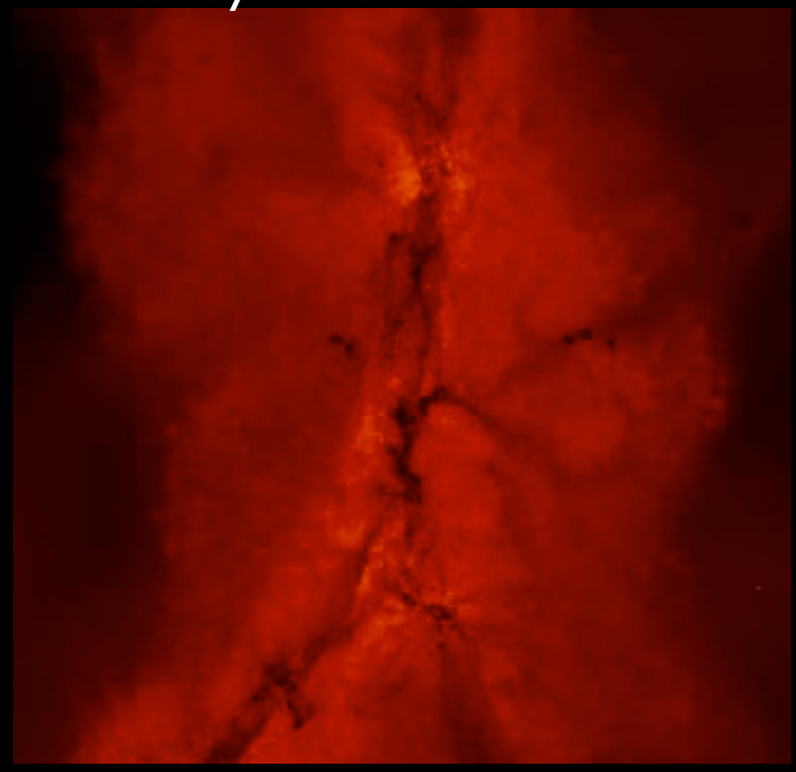
SNe Explode in Density Peaks
(no radiative feedback)



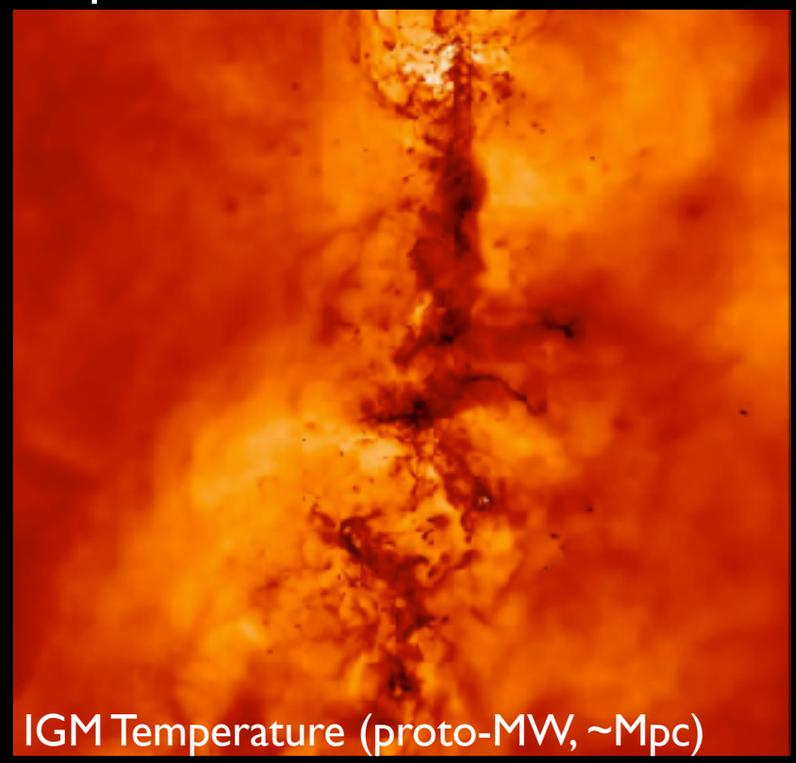
SNe Clustered & Off-Peak
(radiative feedback/pre-processing)



Winds “by hand” ~SFR



Explicit ISM/Feedback



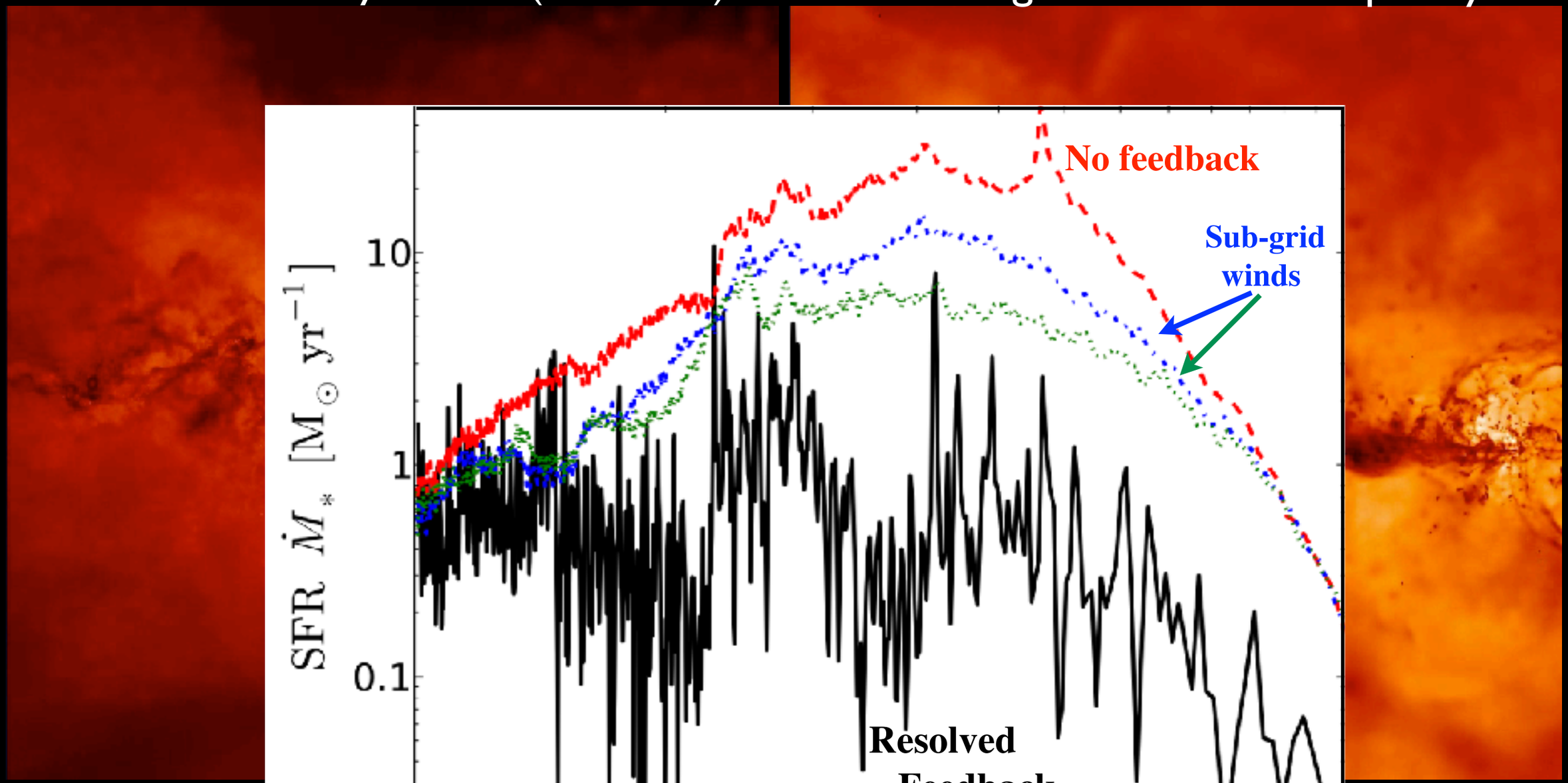
Clustering in Time & Space Matters
(NOW ON GALAXY SCALES)

PFH '14
M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

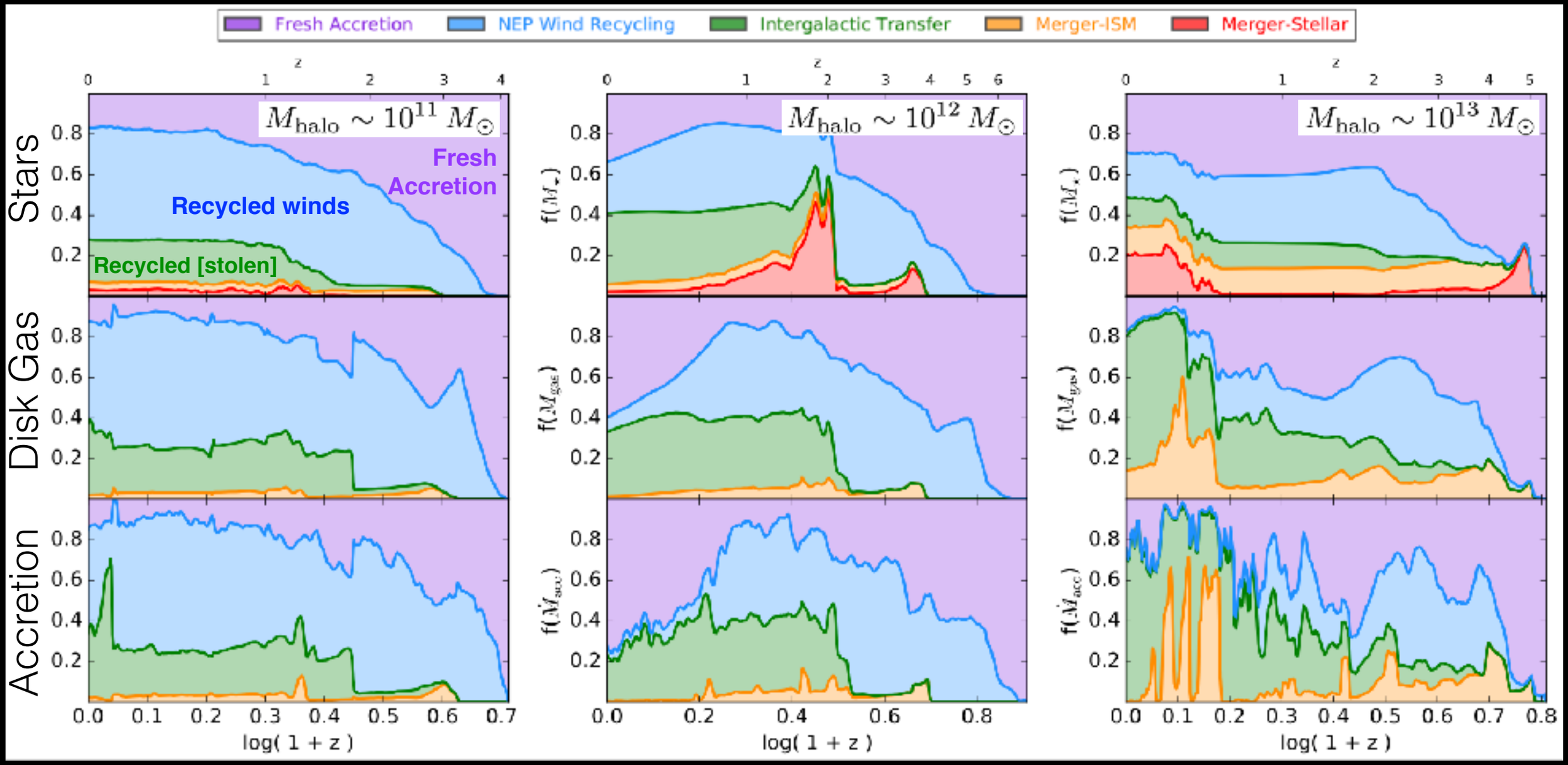
Insert Winds "By Hand" (Sub-Grid)

Following Feedback/ISM Explicitly

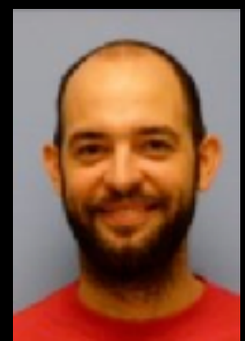


Recycling Matters

MORE IMPORTANT AT LOW-Z, ESPECIALLY FOR DWARFS



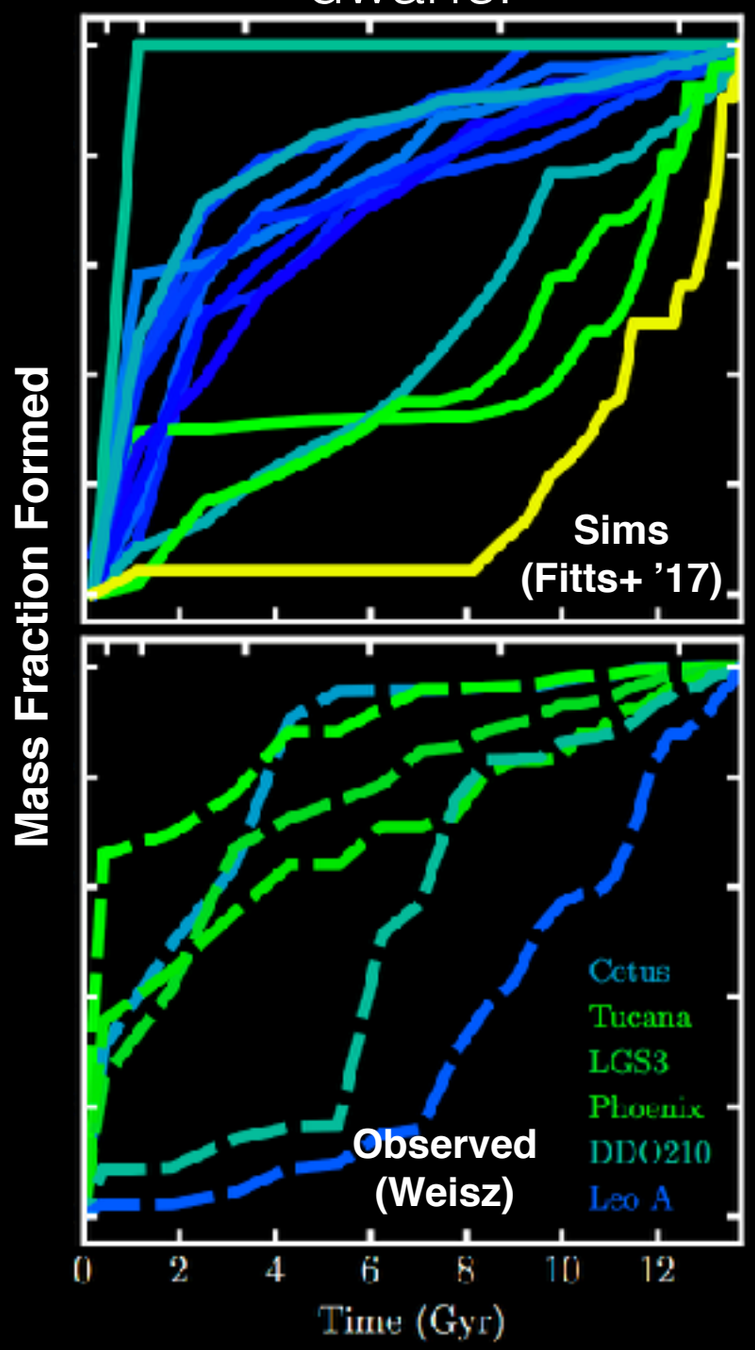
Anglés-Alcázar+17



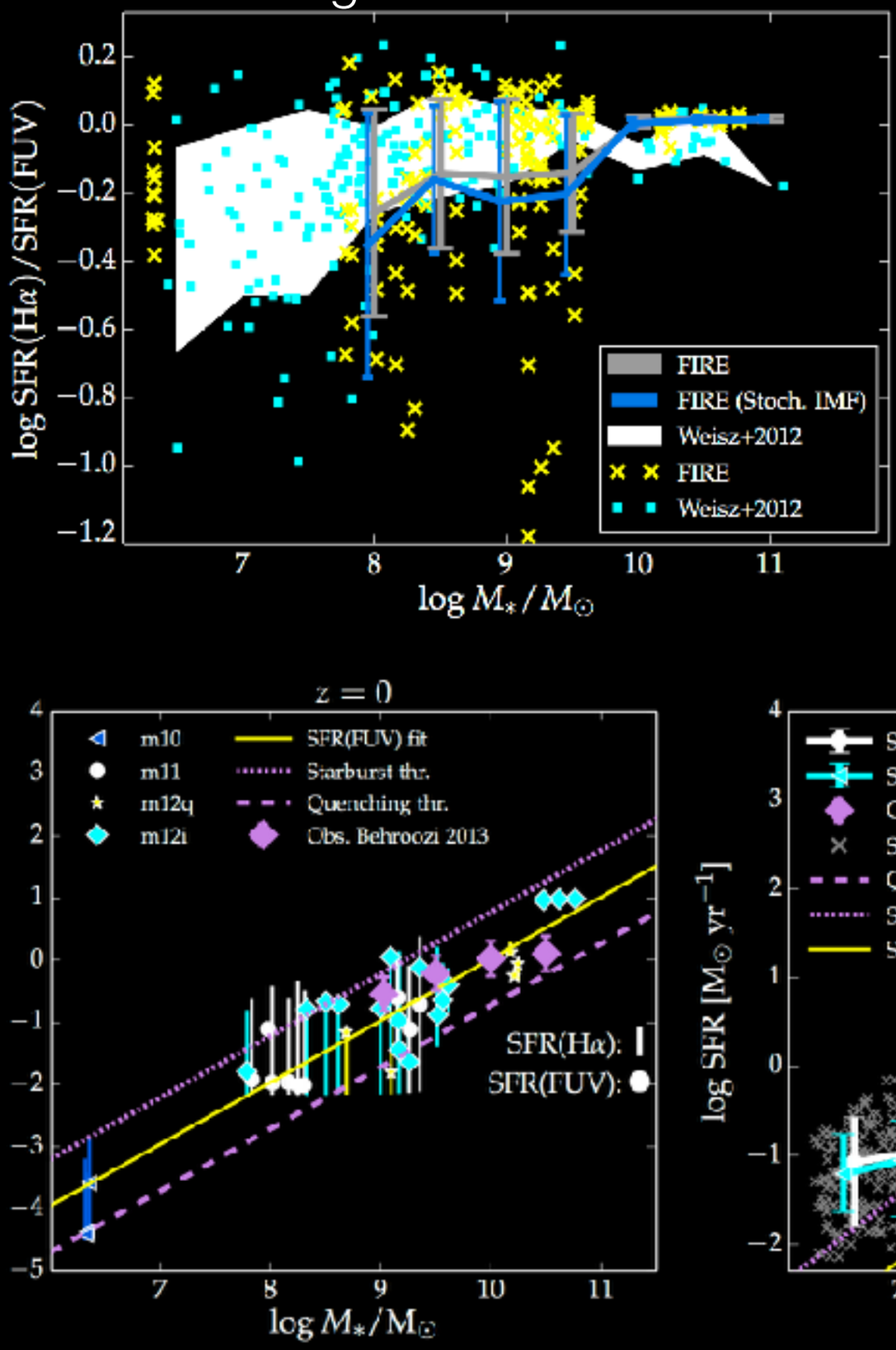
Burstiness & SFR-M_{stars} Relation

M. Sparre
arxiv:1510.03869

dwarfs:



massive galaxies:

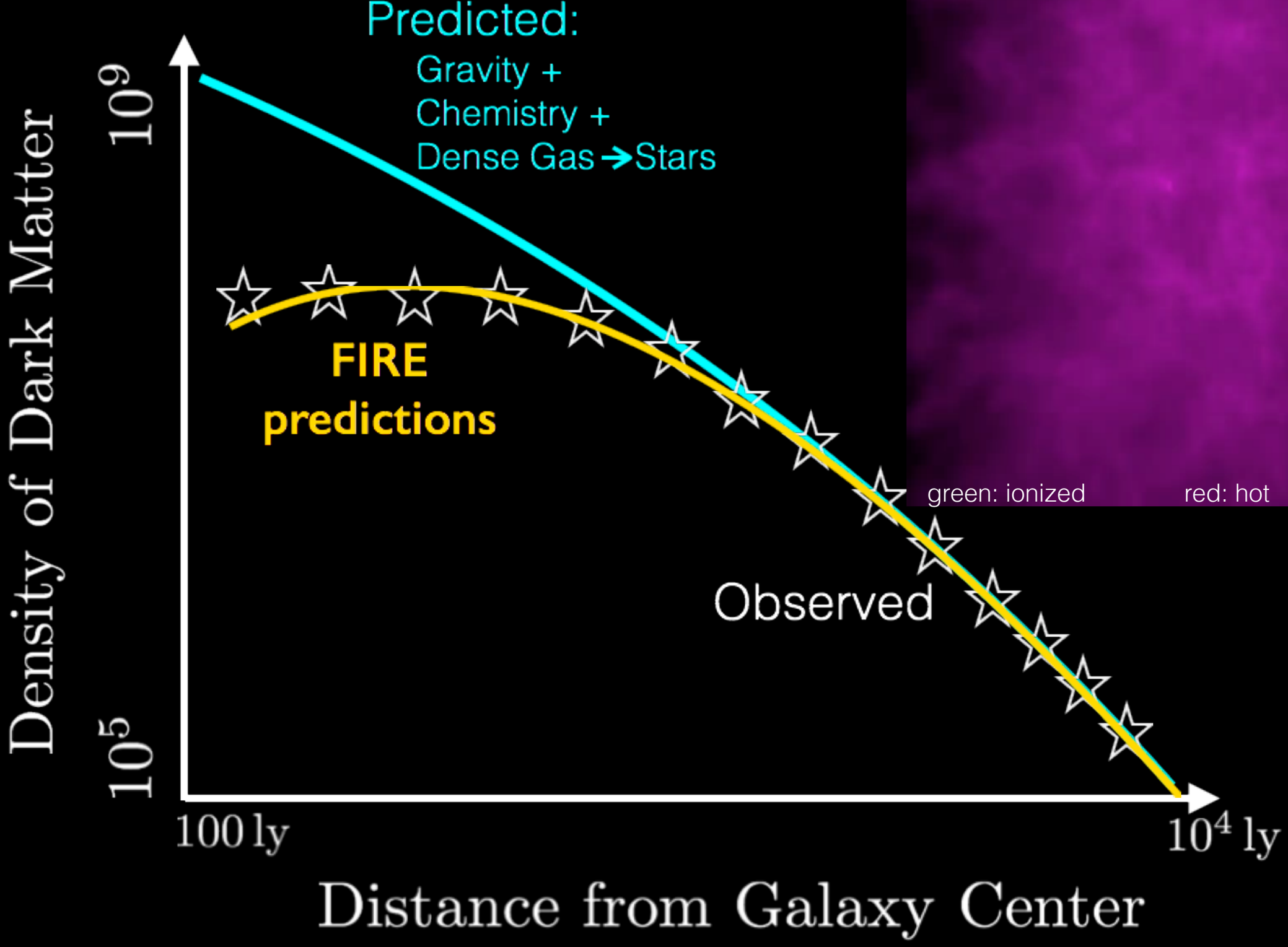


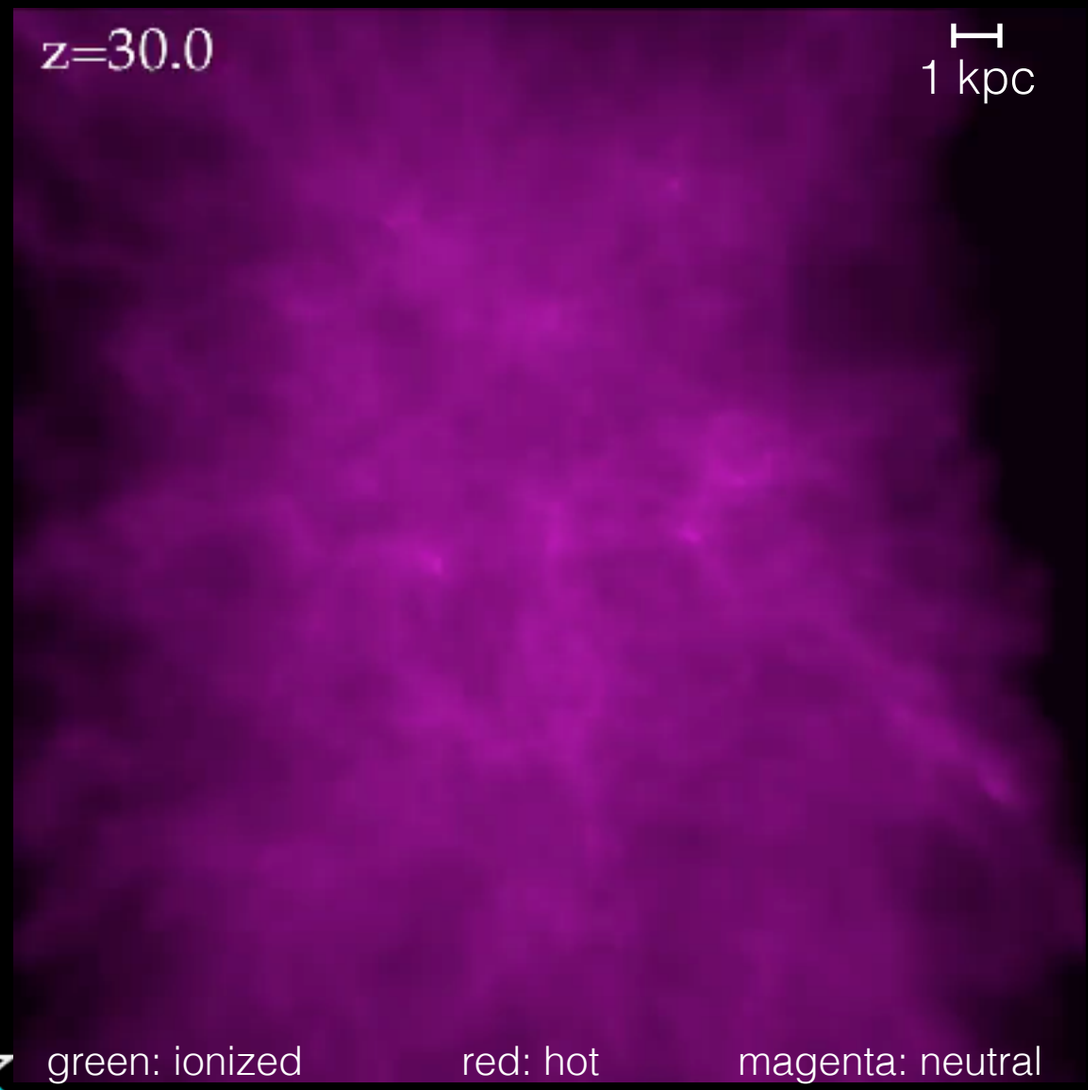
Low-mass scatter is *not* a "hidden variable"

Bursty/Calm Star Formation & Galactic Structure

Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS NECESSARY



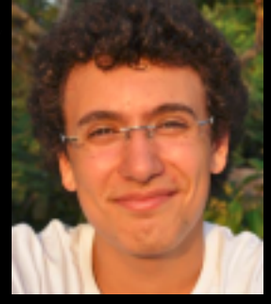


Onorbe et al.
(arXiv:1502.02036)
Chan et al.
(arXiv:1507.02282)
Wheeler et al.
(arXiv:1504.02466)

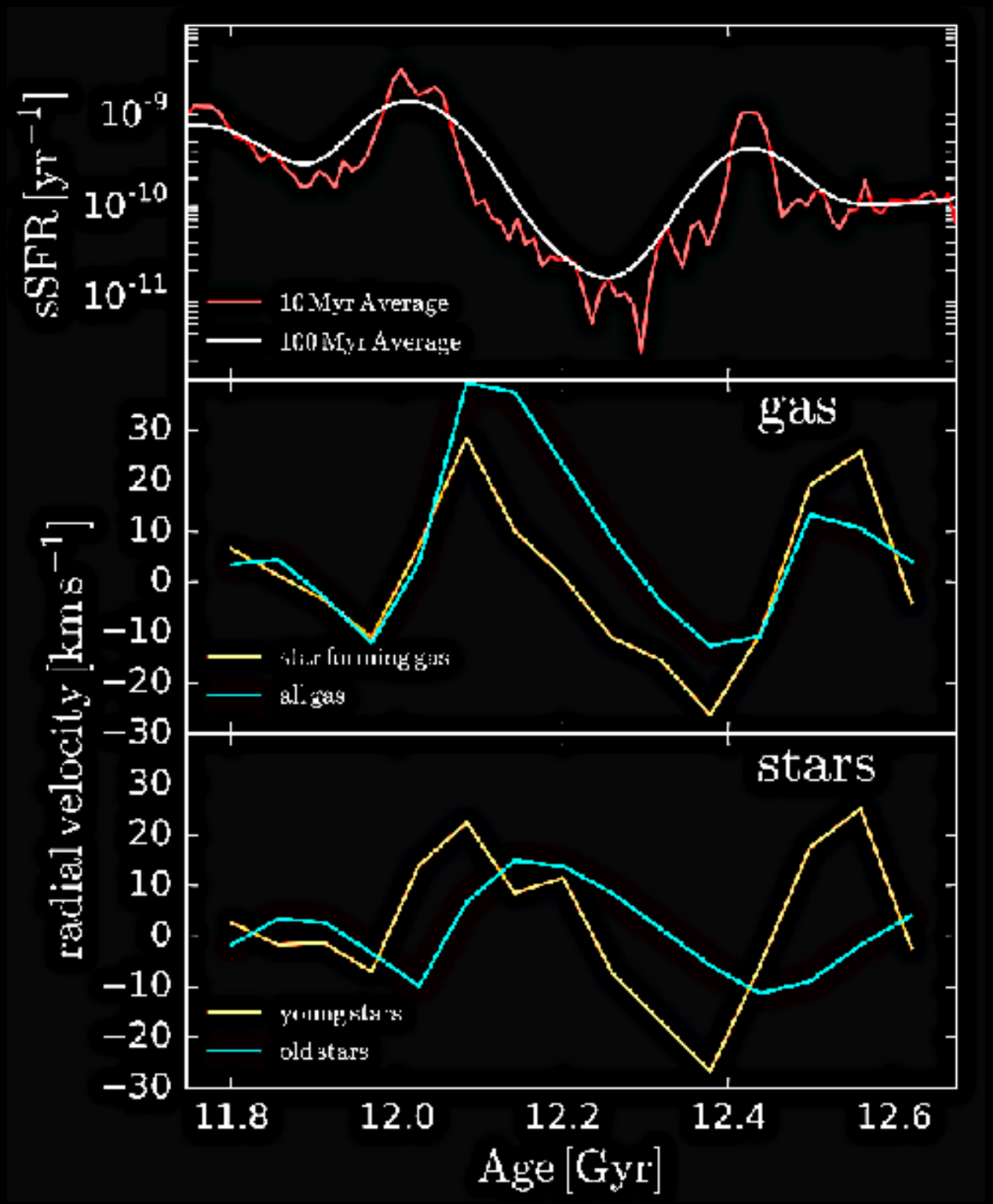
Direct Consequences for Structure

BURSTY SF = STARS MIXED, JUST LIKE DM

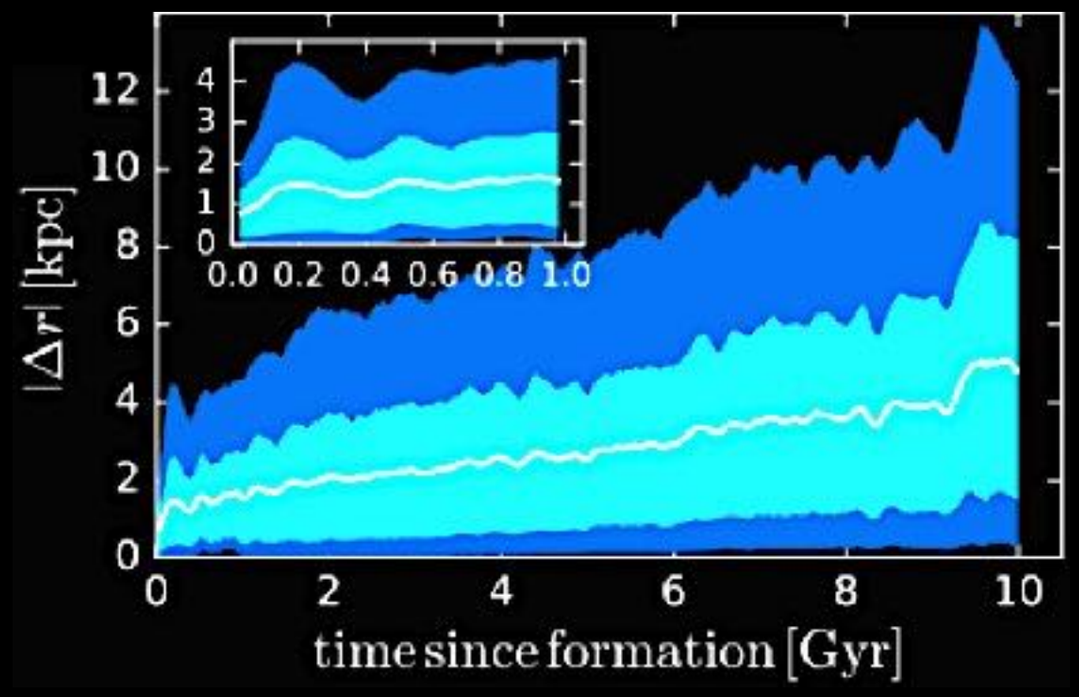
K. El-Badry
(arXiv:1512.01235)



Radial "breathing" in each burst:



Orbits "pumped up"

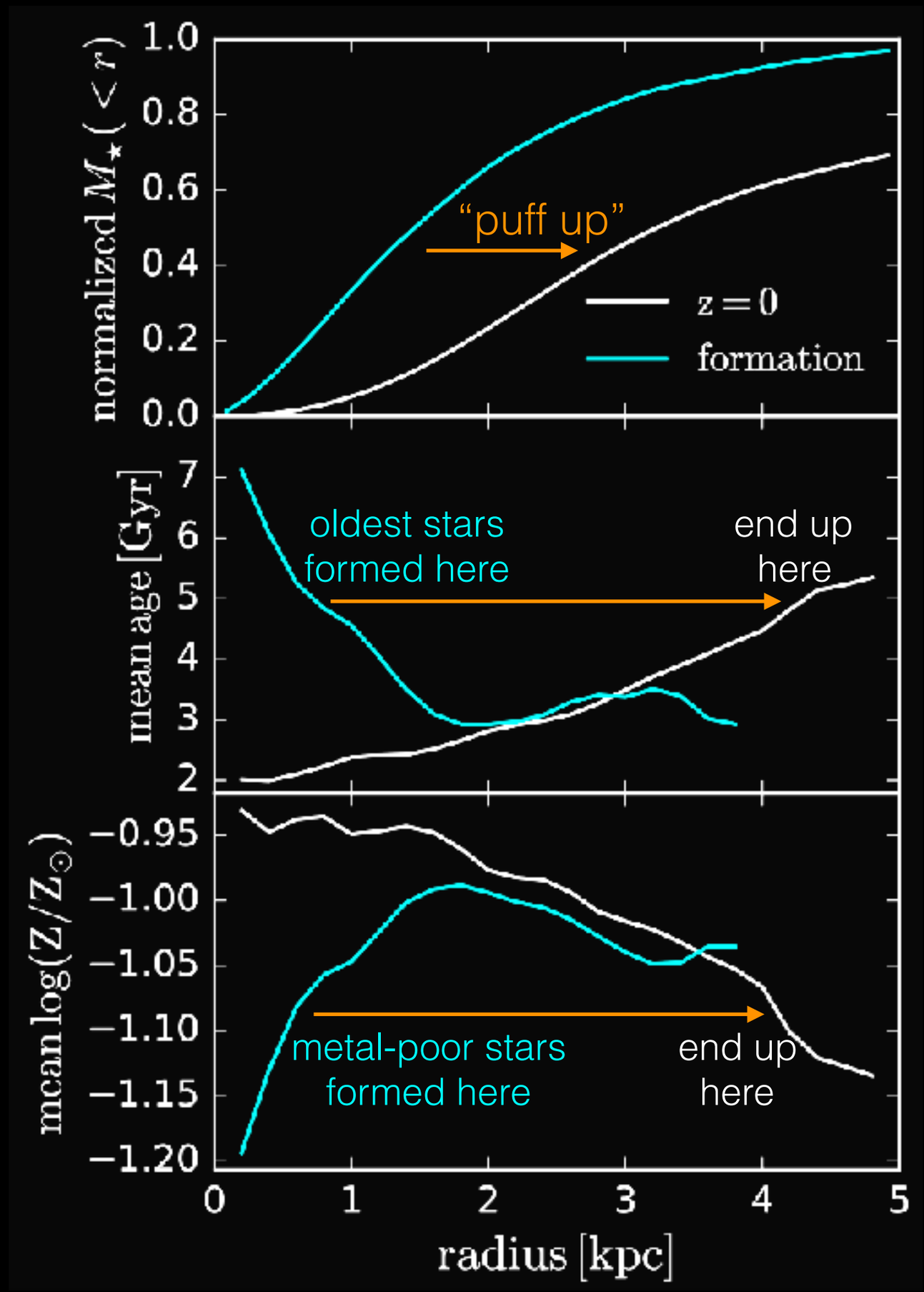


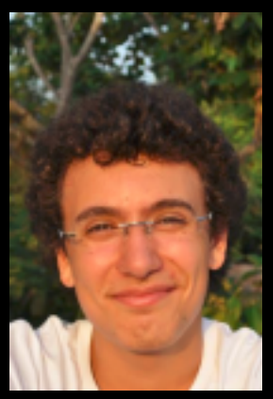
- If DM orbits perturbed, stars are too!

Direct Consequences for Structure

BURSTY SF = STARS MIXED, JUST LIKE DM

- If DM orbits perturbed, stars are too!
  - Radial anisotropy
  - Gradients "wiped out"
  - Galactic radii *oscillate*



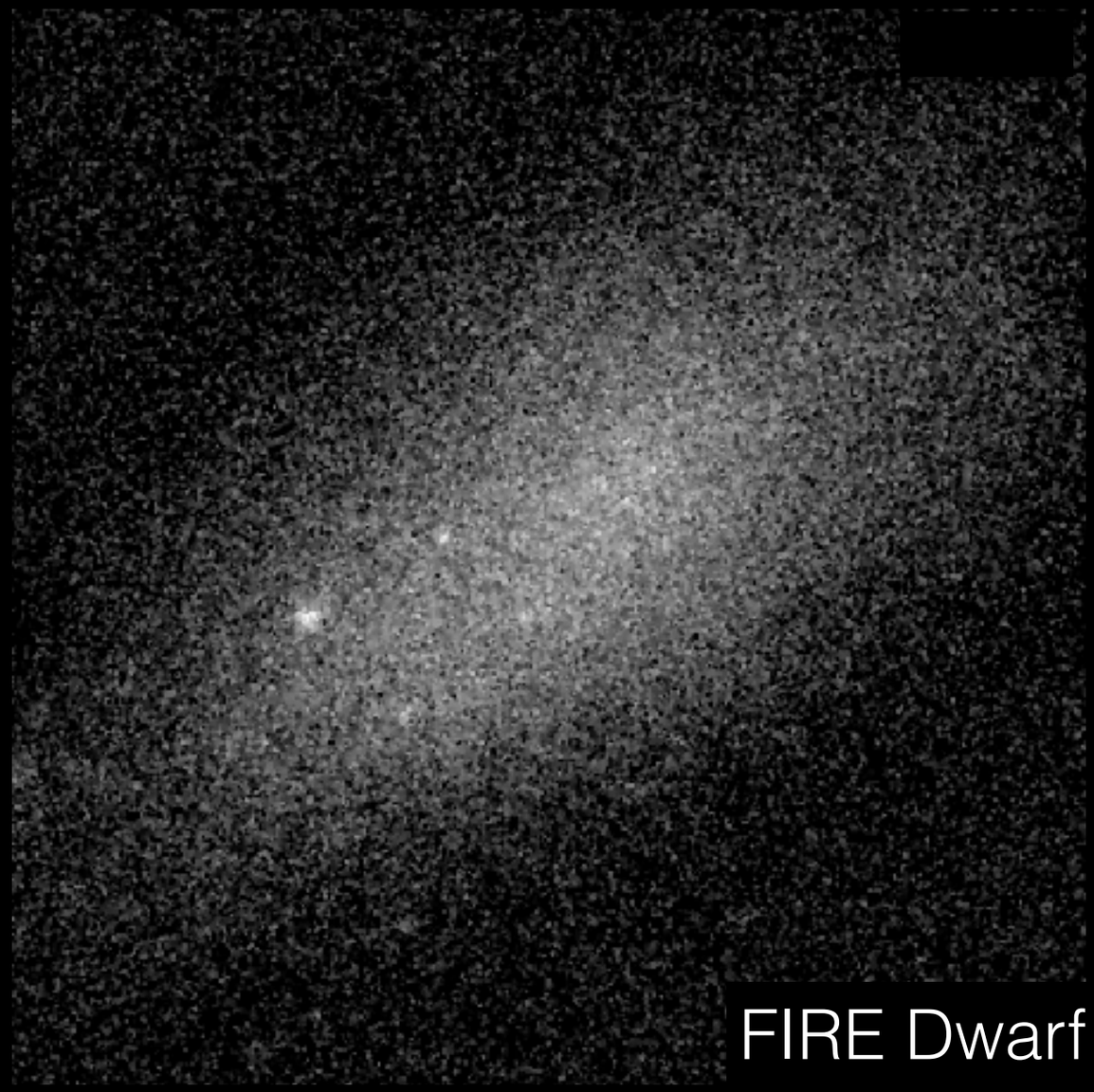


Kareem El-Badry
arXiv:1512.01235

New Classes of Galaxies

ULTRA-DIFFUSE SYSTEMS: THE NEW "NORMAL"

TK Chan (prep)



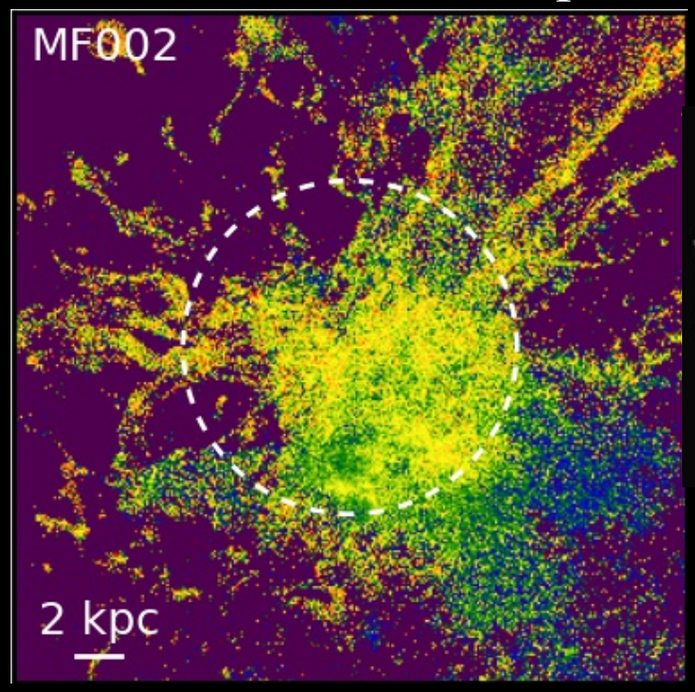
Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

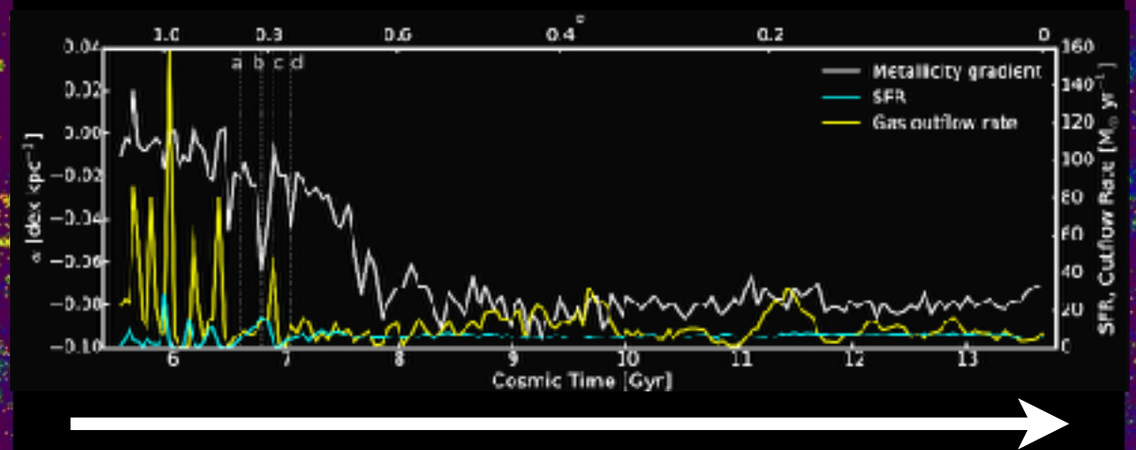
BUILDUP OF METALLICITY GRADIENTS

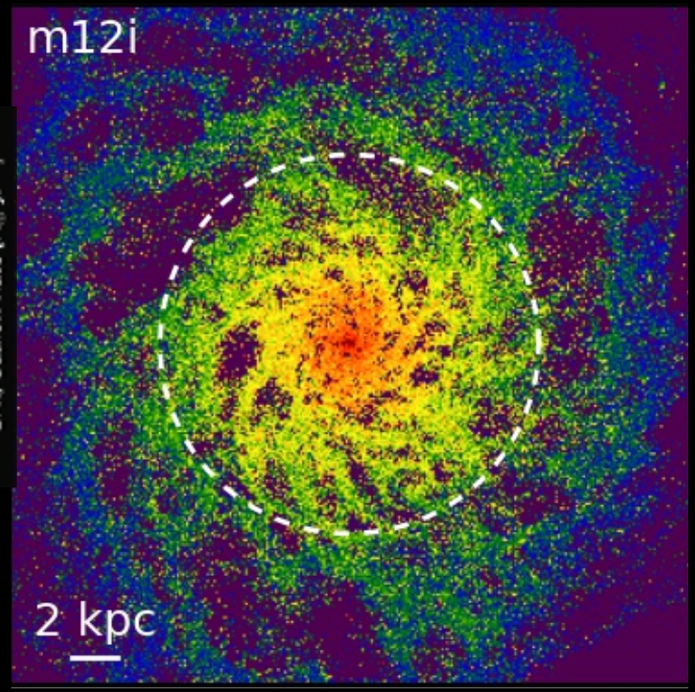
Xiangcheng Ma
(arXiv:1610.03498)

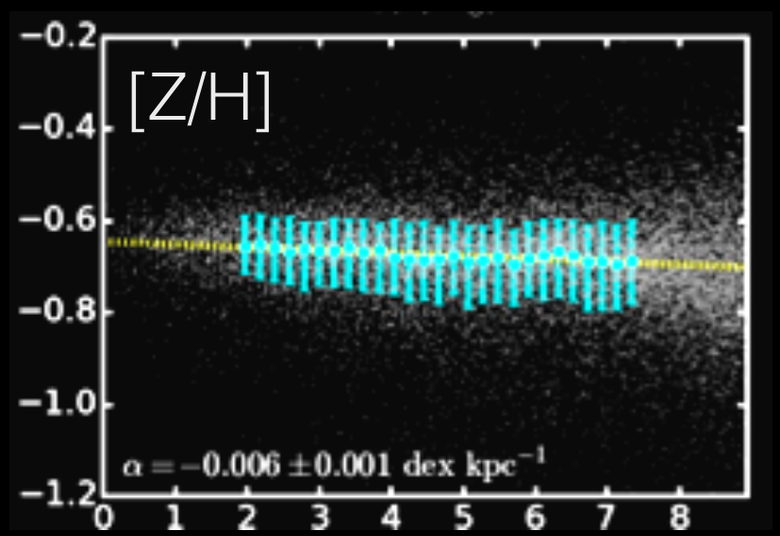
"feedback-dominated" phase

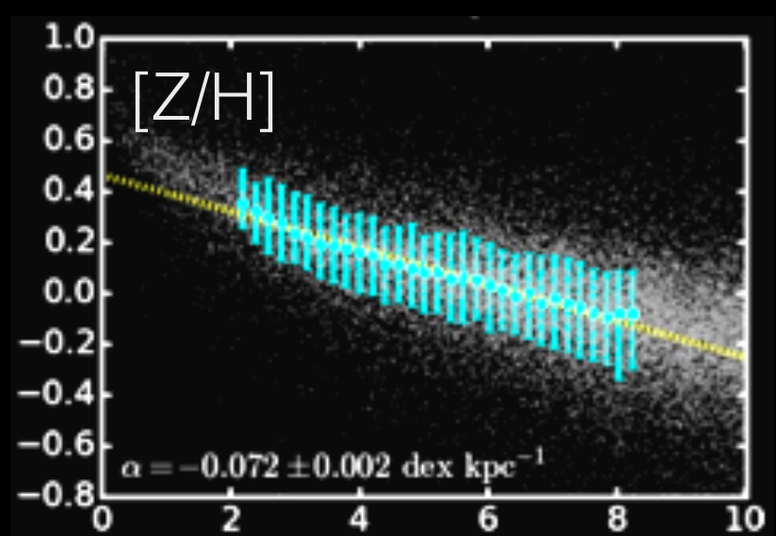
"gravity-dominated" phase







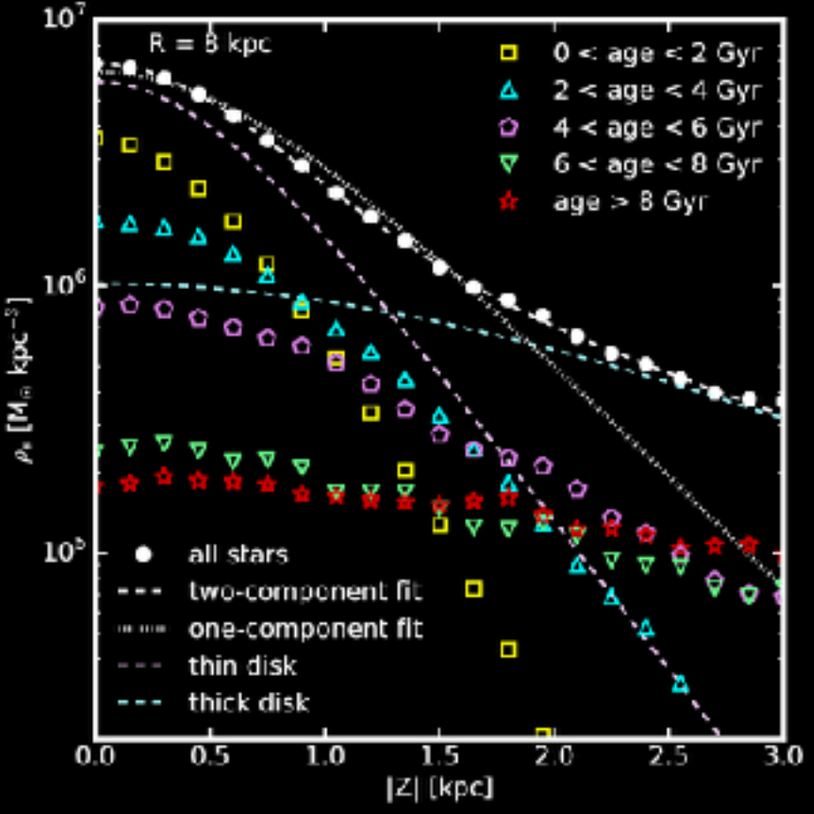


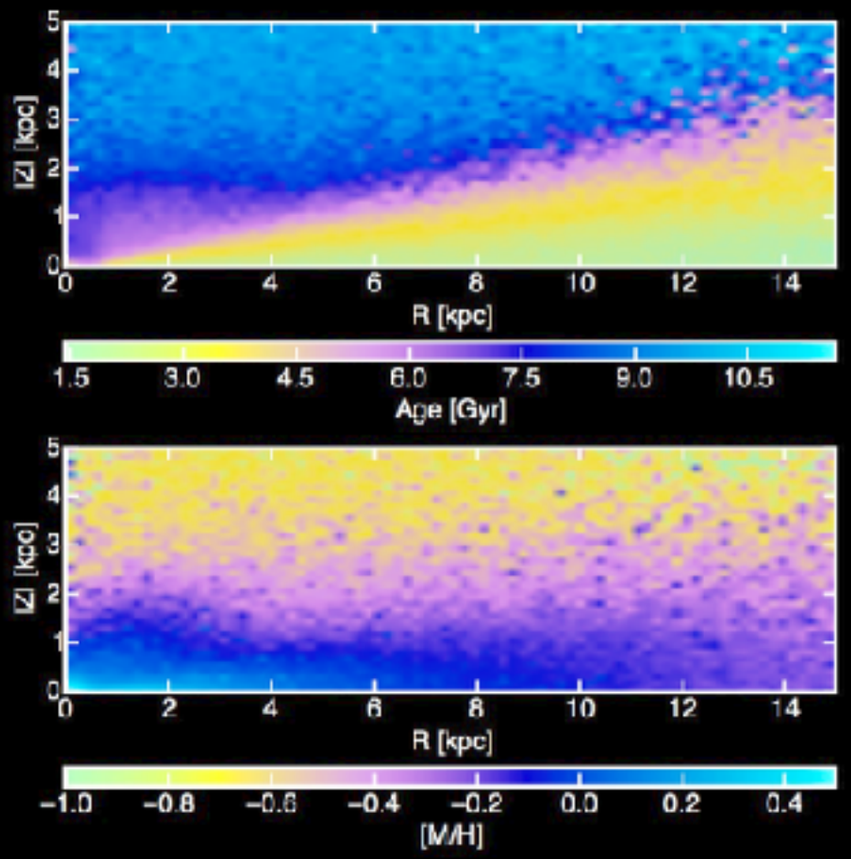


Transition from Feedback-Dominated to "Calm" (Gravity-Dominated)

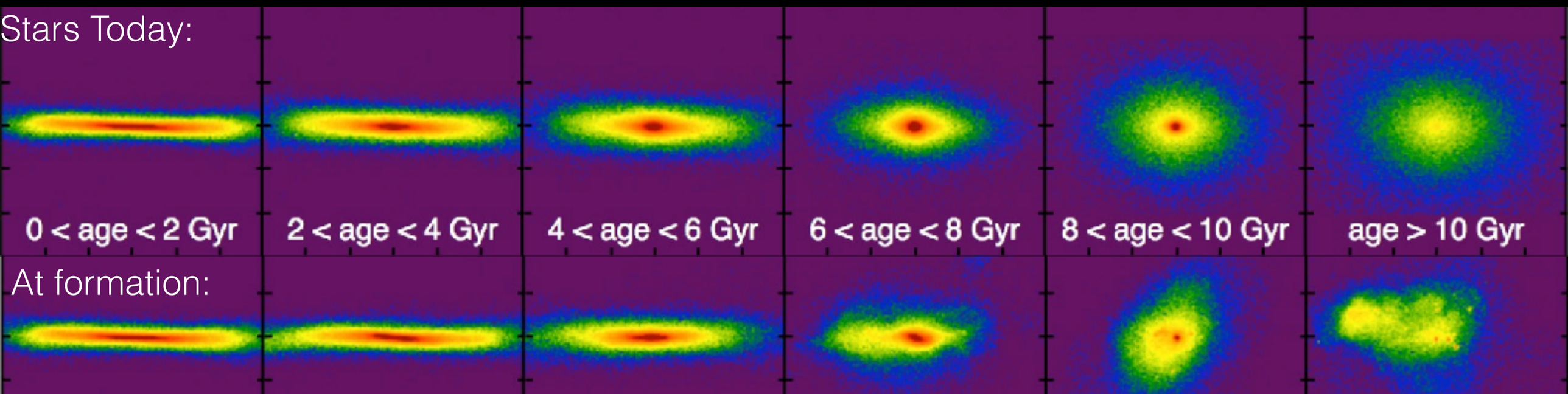
THICK -> THIN DISK

Xiangcheng Ma
(arXiv:1608.04133)
Ana Bonaca
(arXiv:1704.05463)

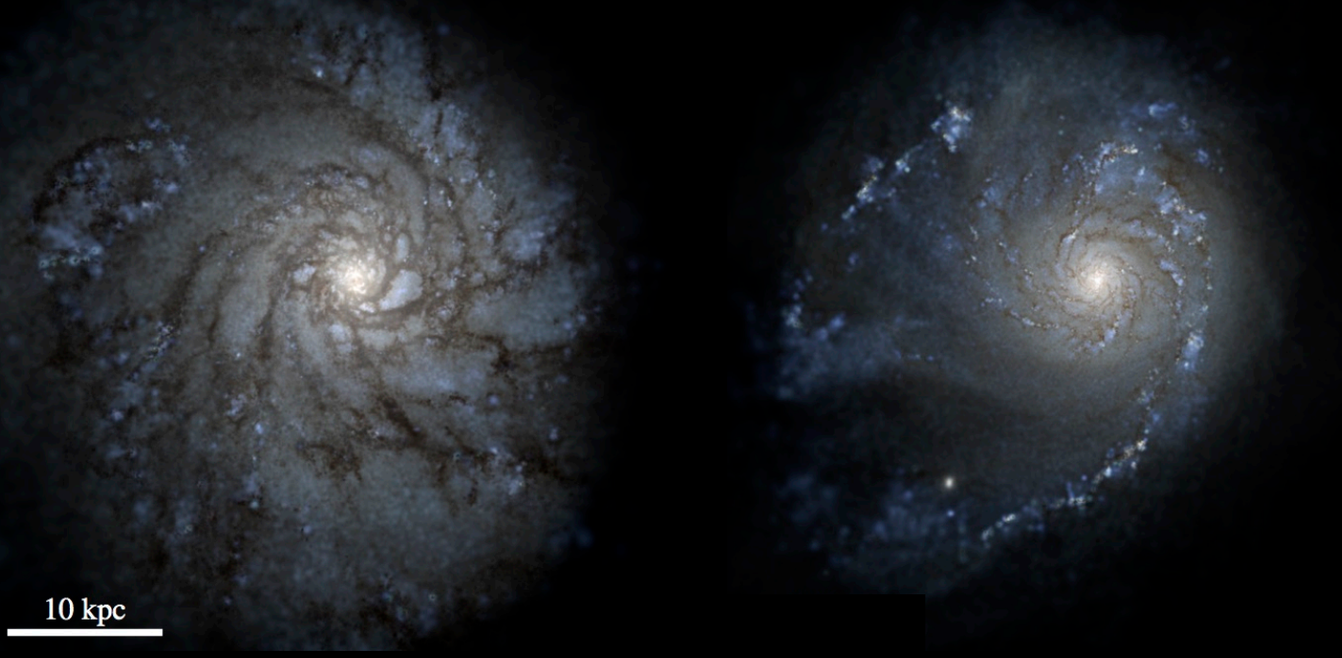




Detailed vertical+radial
abundance gradients & kinematics
of thin/thick disk populations



Thin Disks Emerge Naturally…
but when/where?

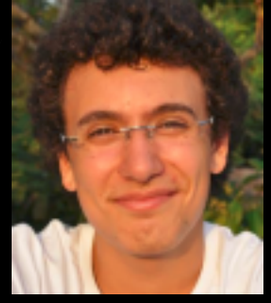


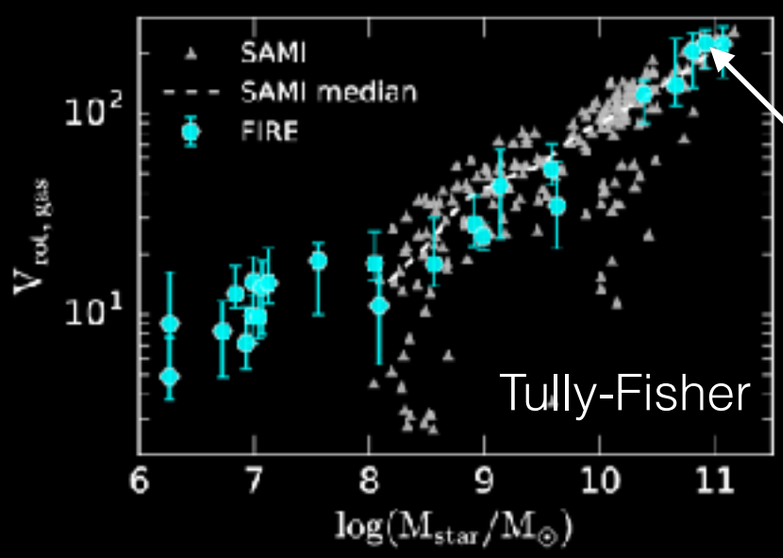
Garrison-Kimmel
et al., in prep

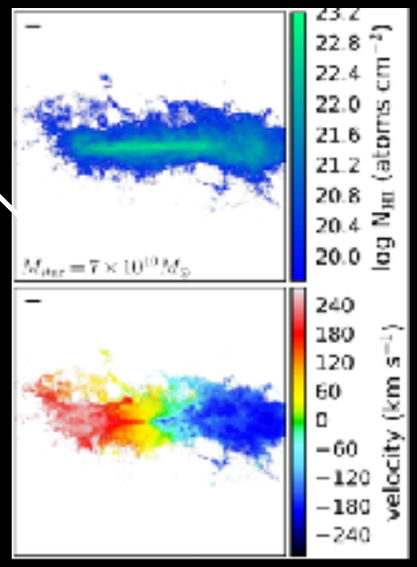
Angular Momentum of Gas+Stars

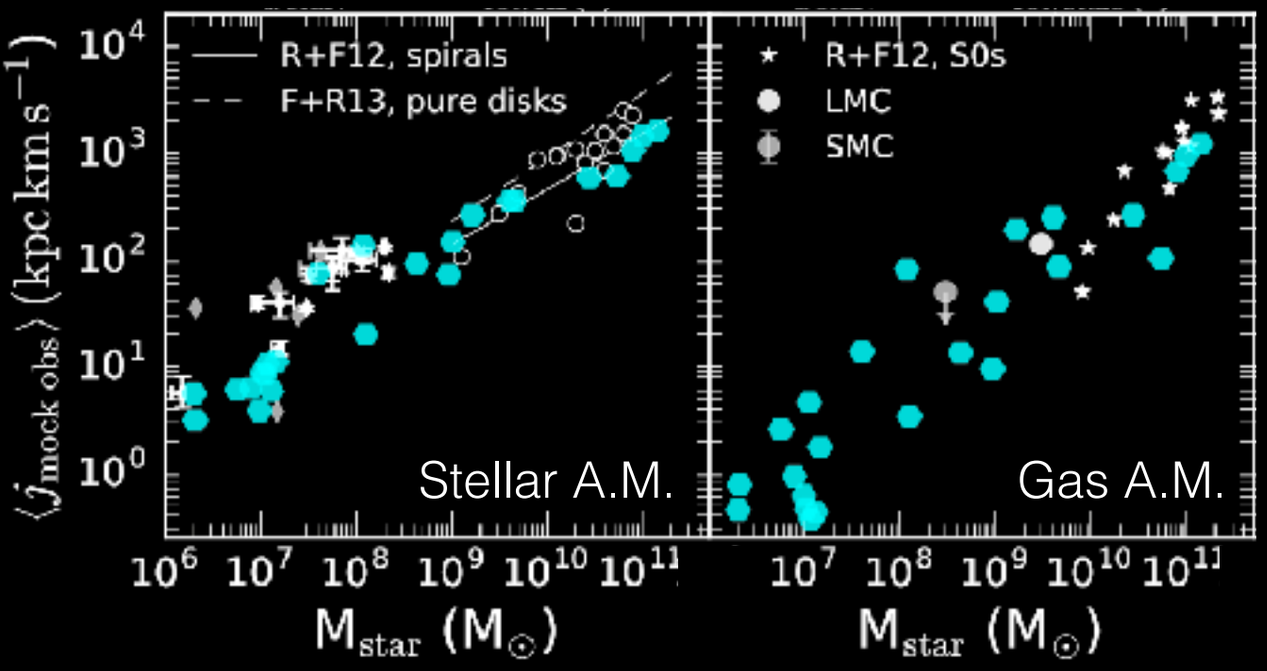
WHY DO DWARFS NOT HAVE (THIN) DISKS?

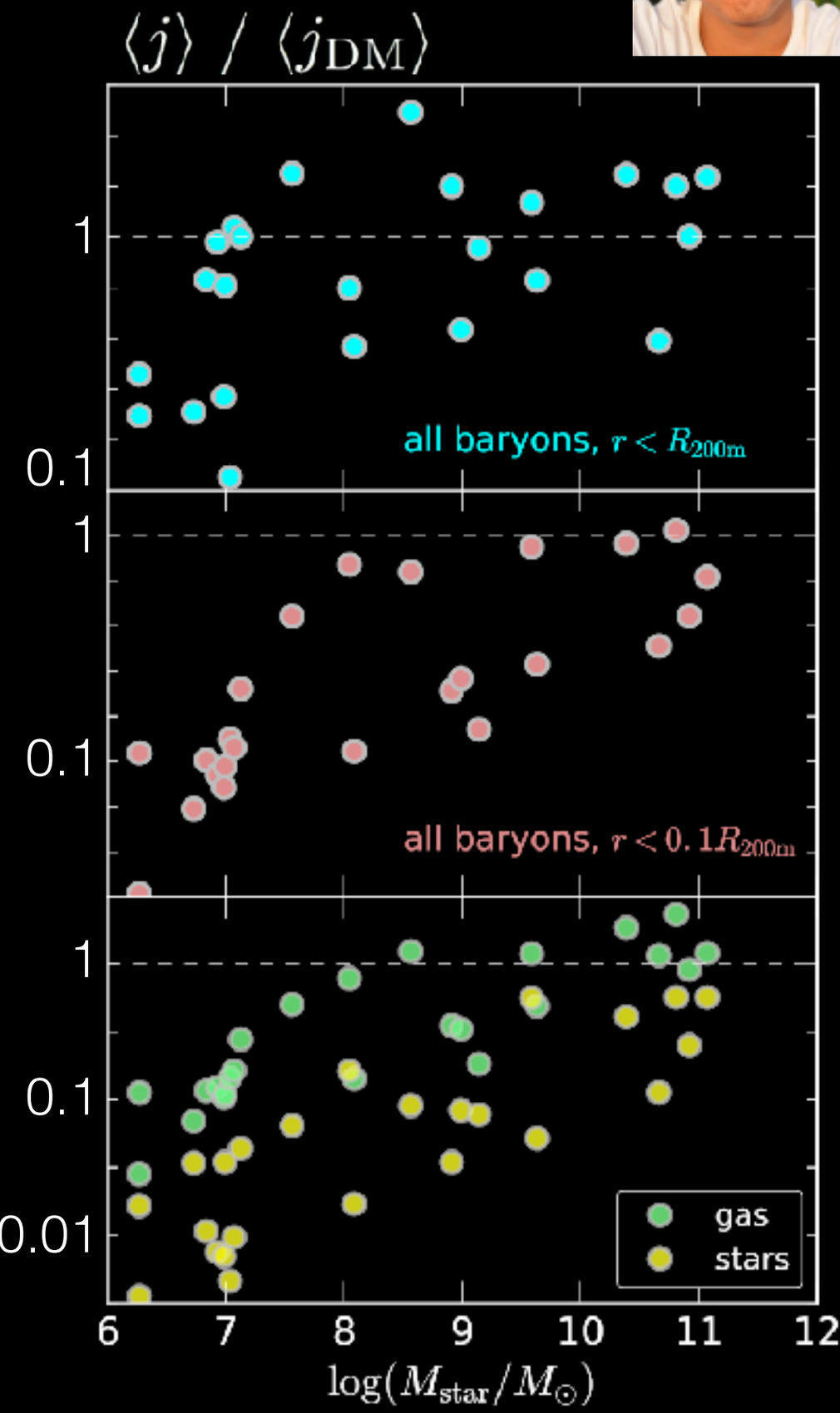
Kareem El-Badry
(arXiv:1705.10321)







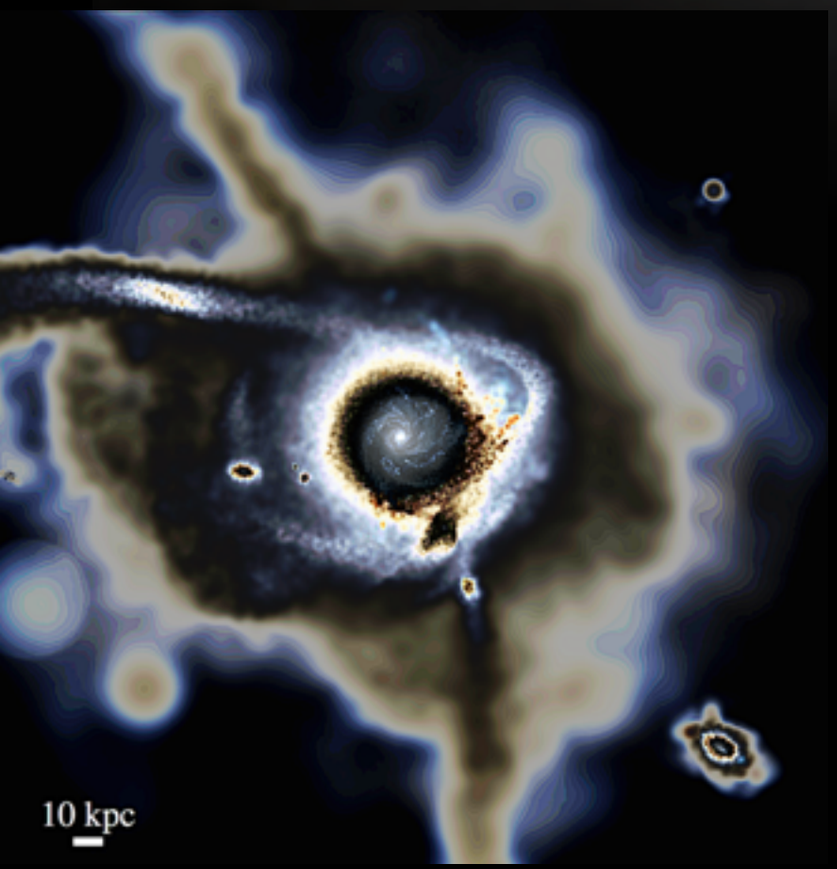


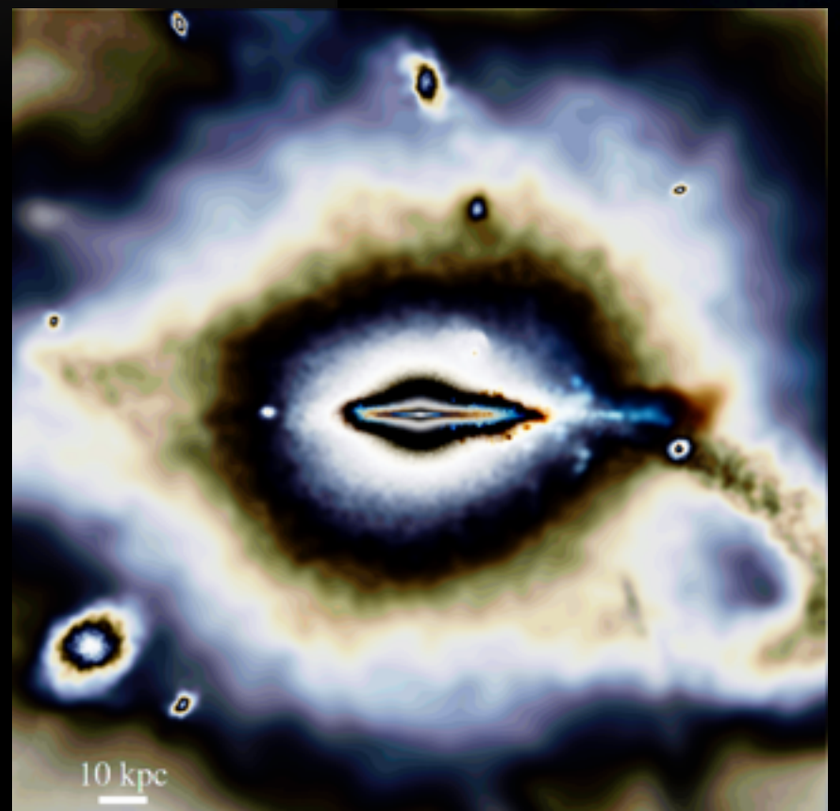


- Thick/irregular [clumpy+bursts+pressure]
- Suppressed late-time accretion [UVB+FB]

Halo Structure

Mock GAIA Catalogues with ~100,000,000 Stars in the (Simulated) Galaxy



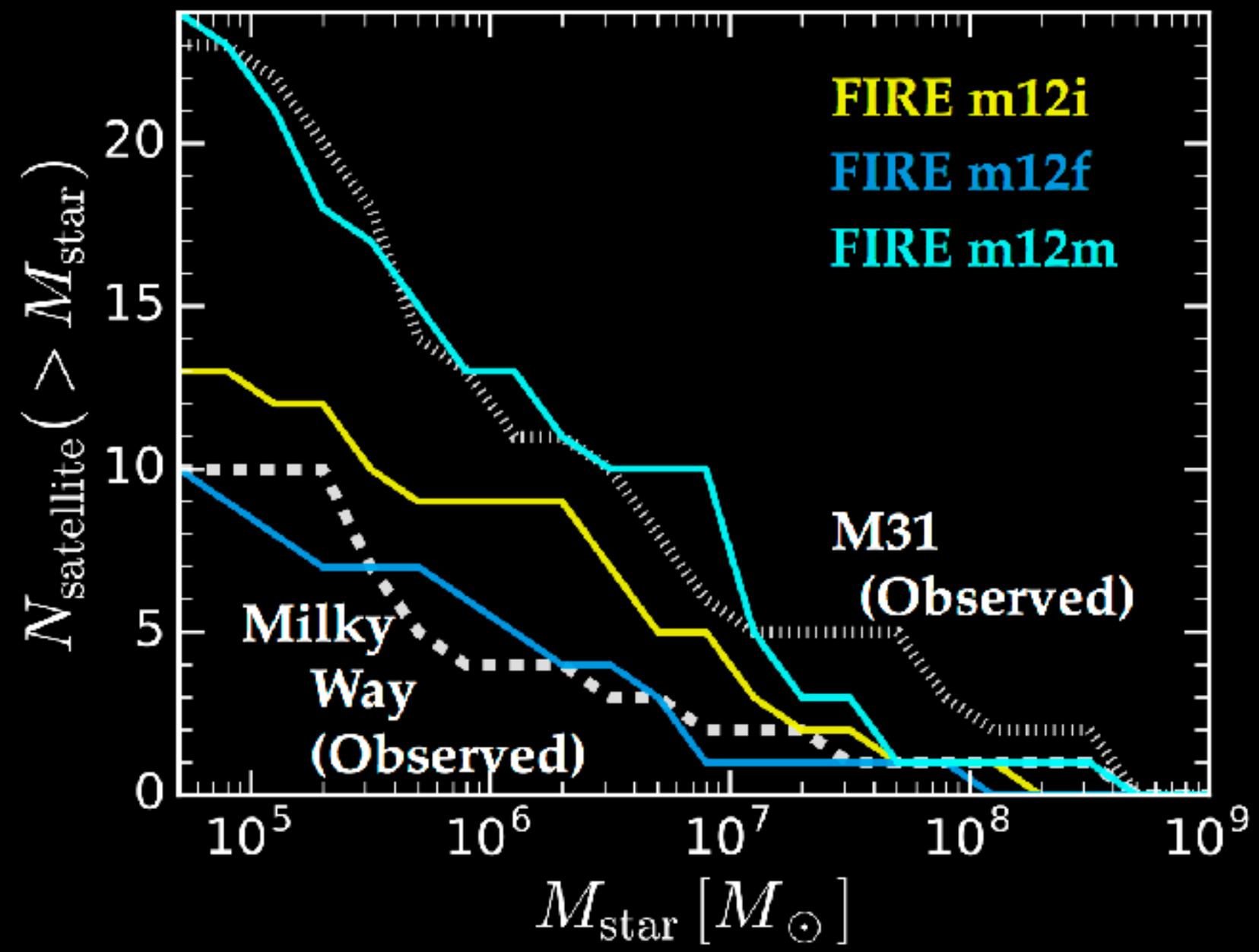


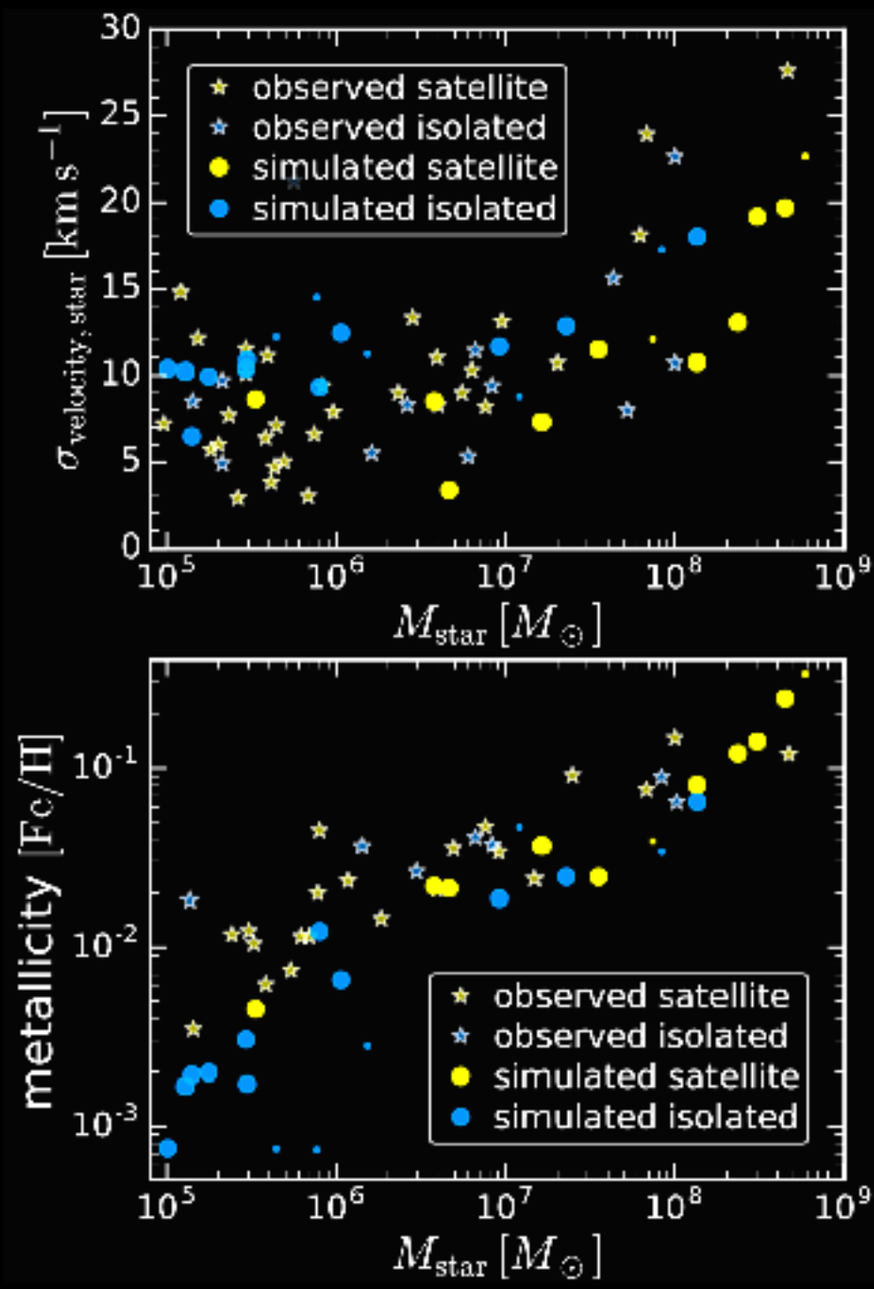
Sanderson et al. (in prep)

Failures No More

FEEDBACK SUPPRESSES STAR FORMATION AND DENSITIES

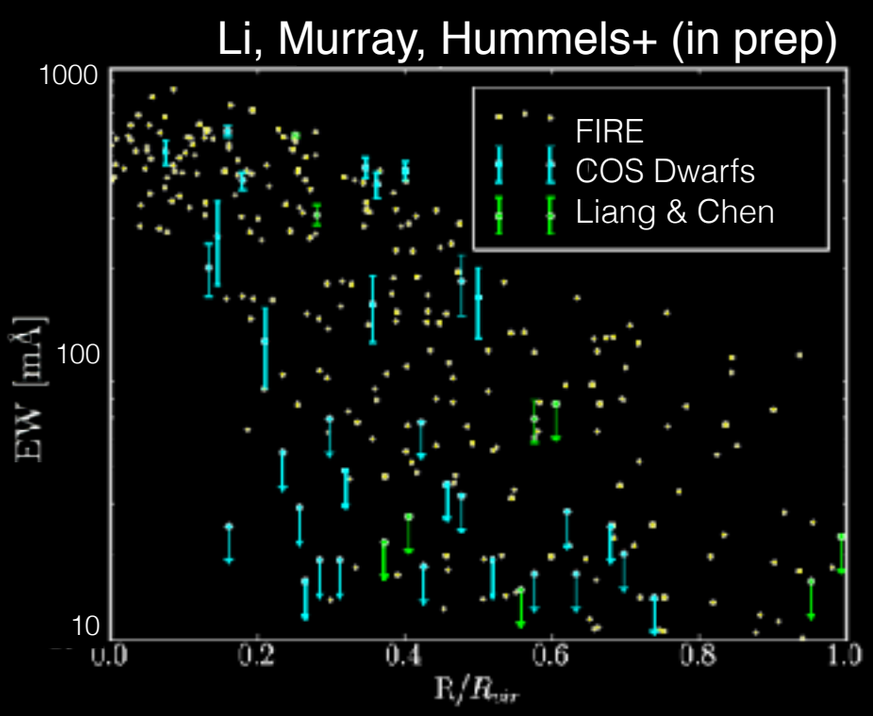
Wetzel + I. Escala (prep)

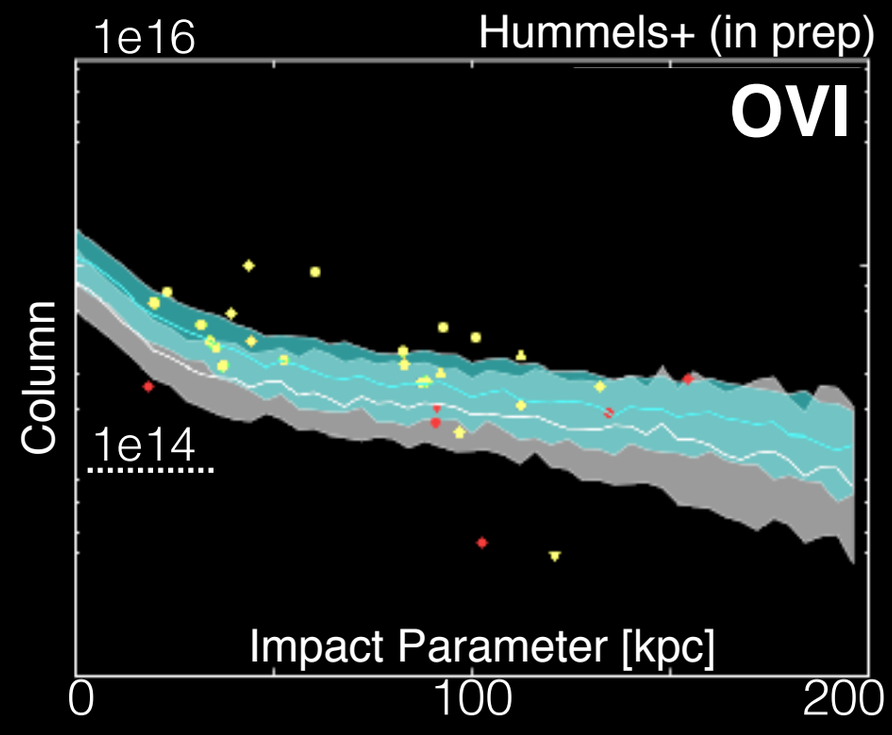




Cameron
Hummels
+ Bili Dong

Consequences for CGM Observables



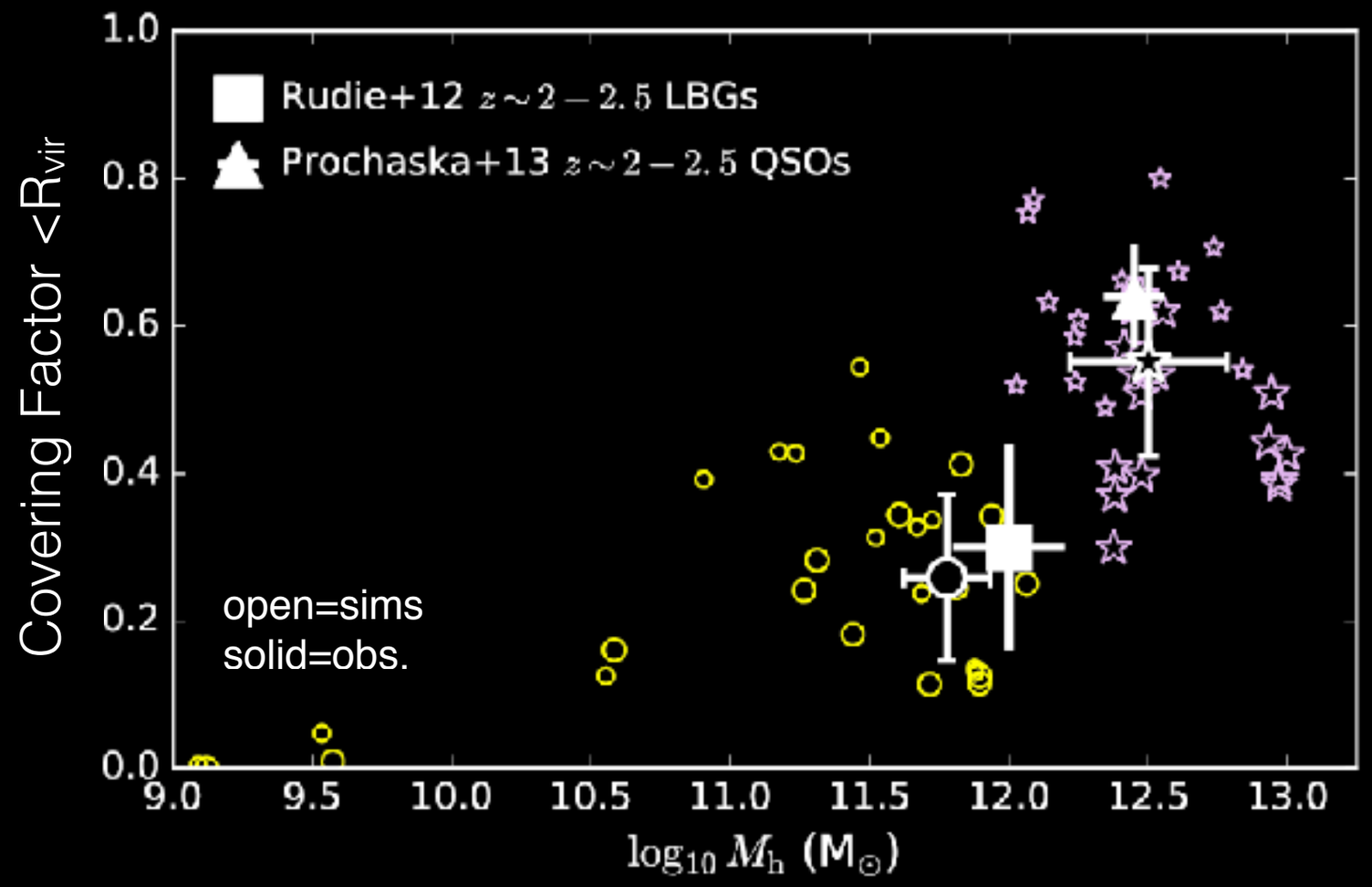


Lyman Limit Covering Factors

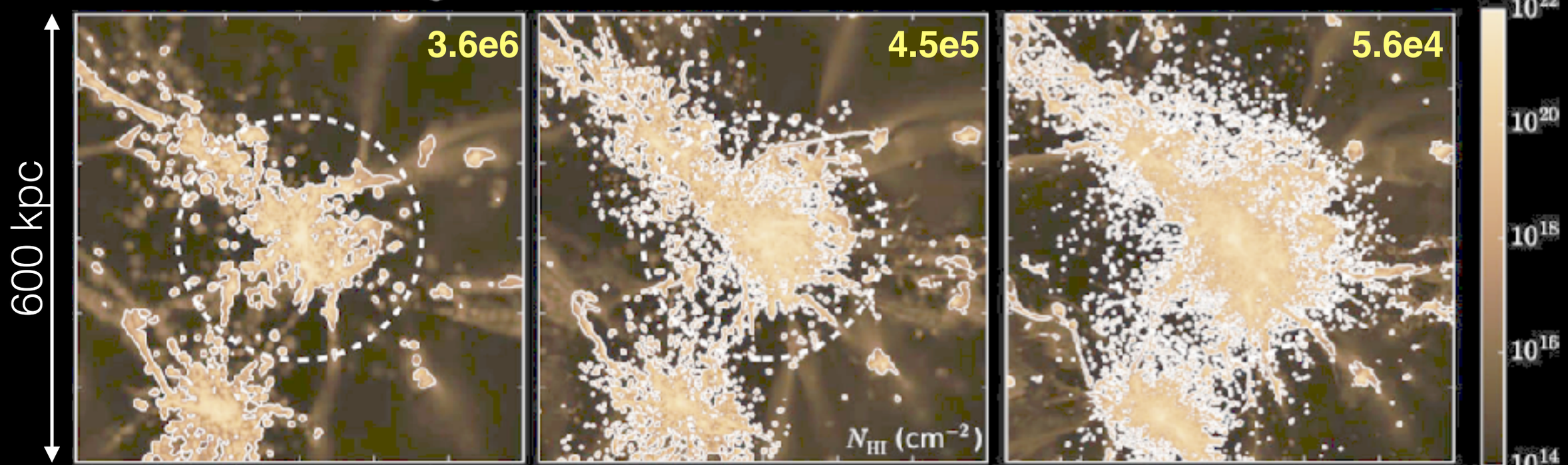
WINDS IMPORTANT, RESOLUTION KEY *FOR THE WINDS*

Faucher-Giguere+ ’15,16

- No AGN needed
- Satellites contribute
- Winds depend on clustered SF, resolved ISM structure



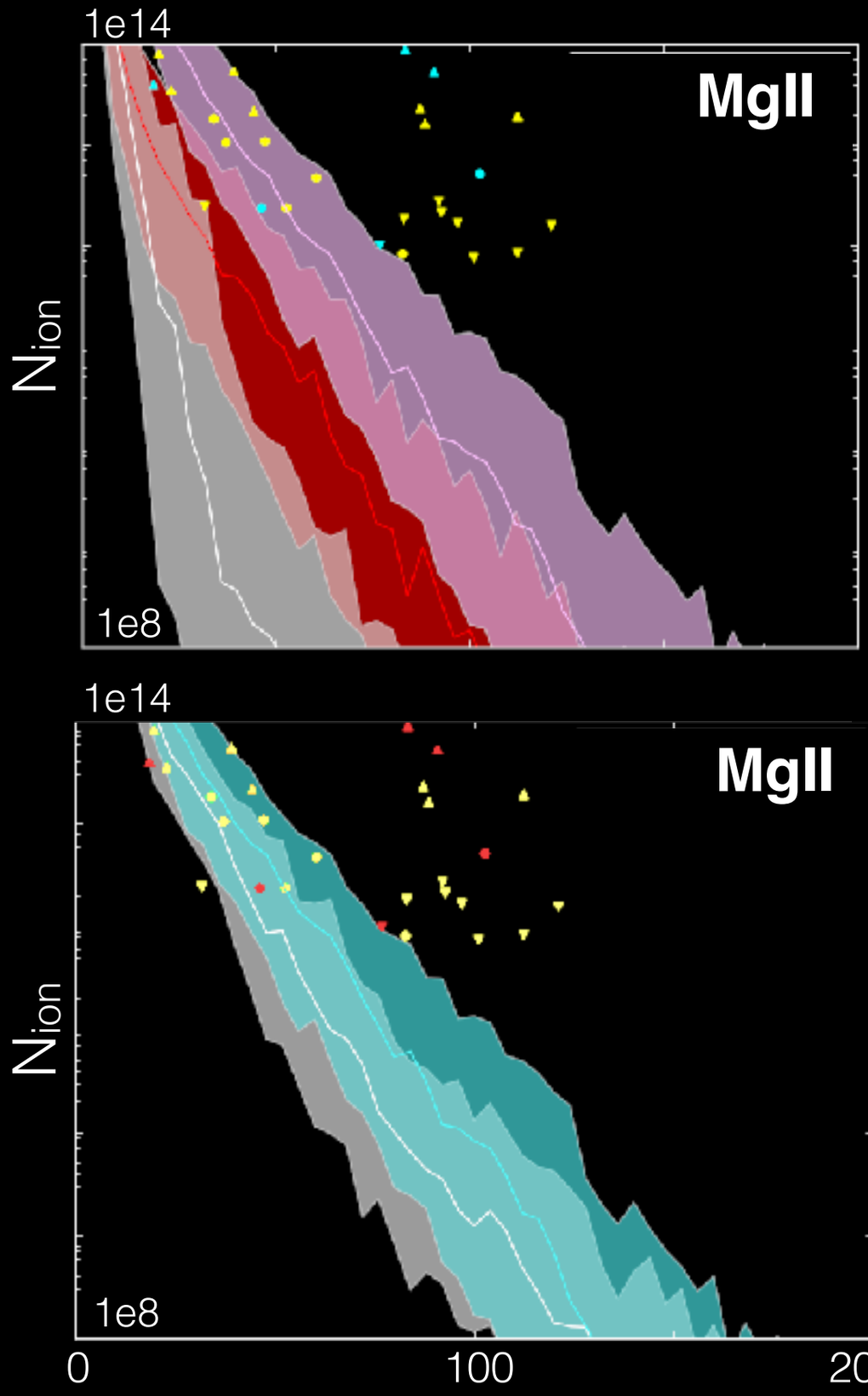
Mass resolution [$M_\odot$]:

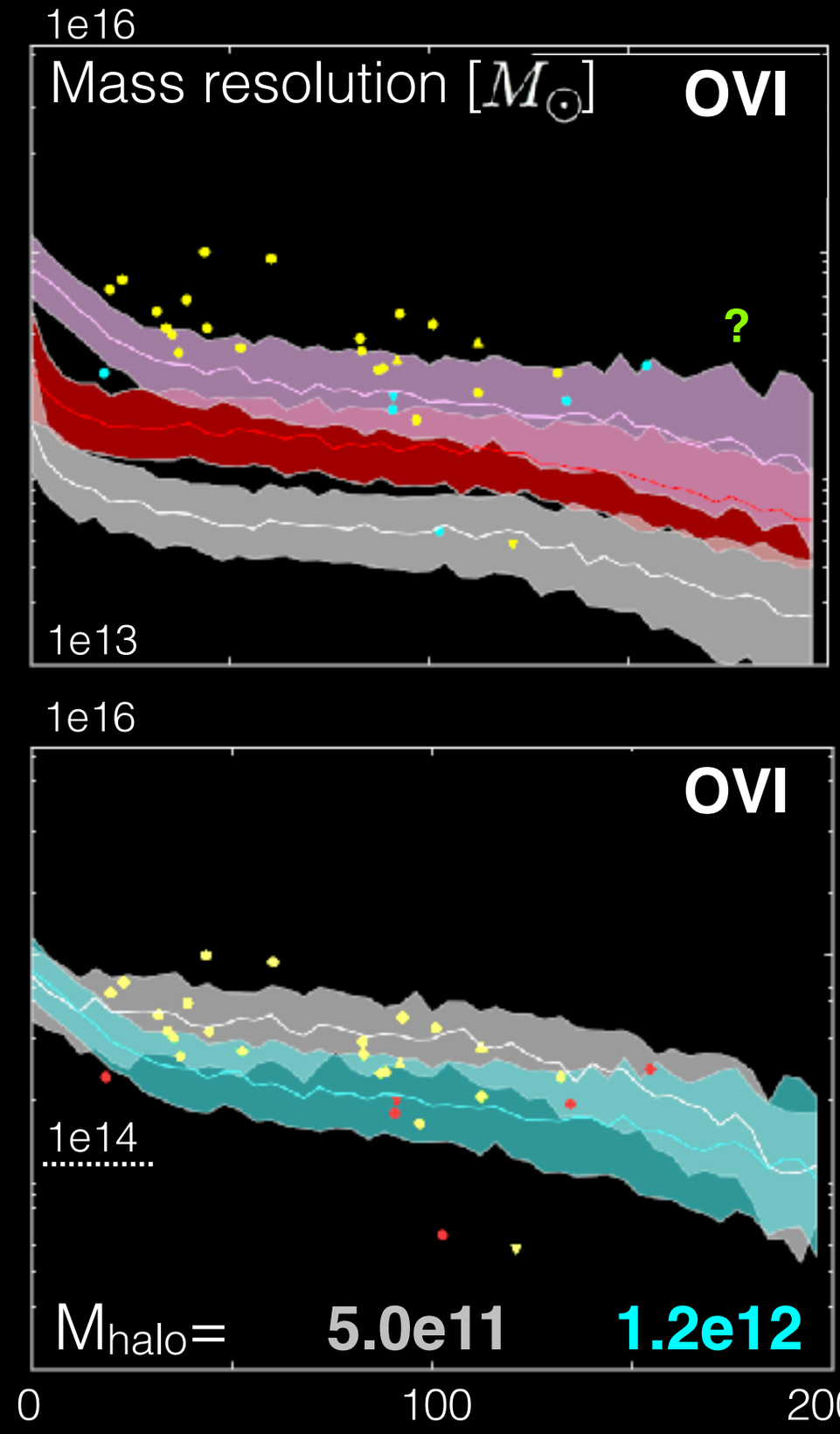


Metals in the CGM at L*: Resolution Matters

MASS DOES TOO

Cameron Hummels (in prep)

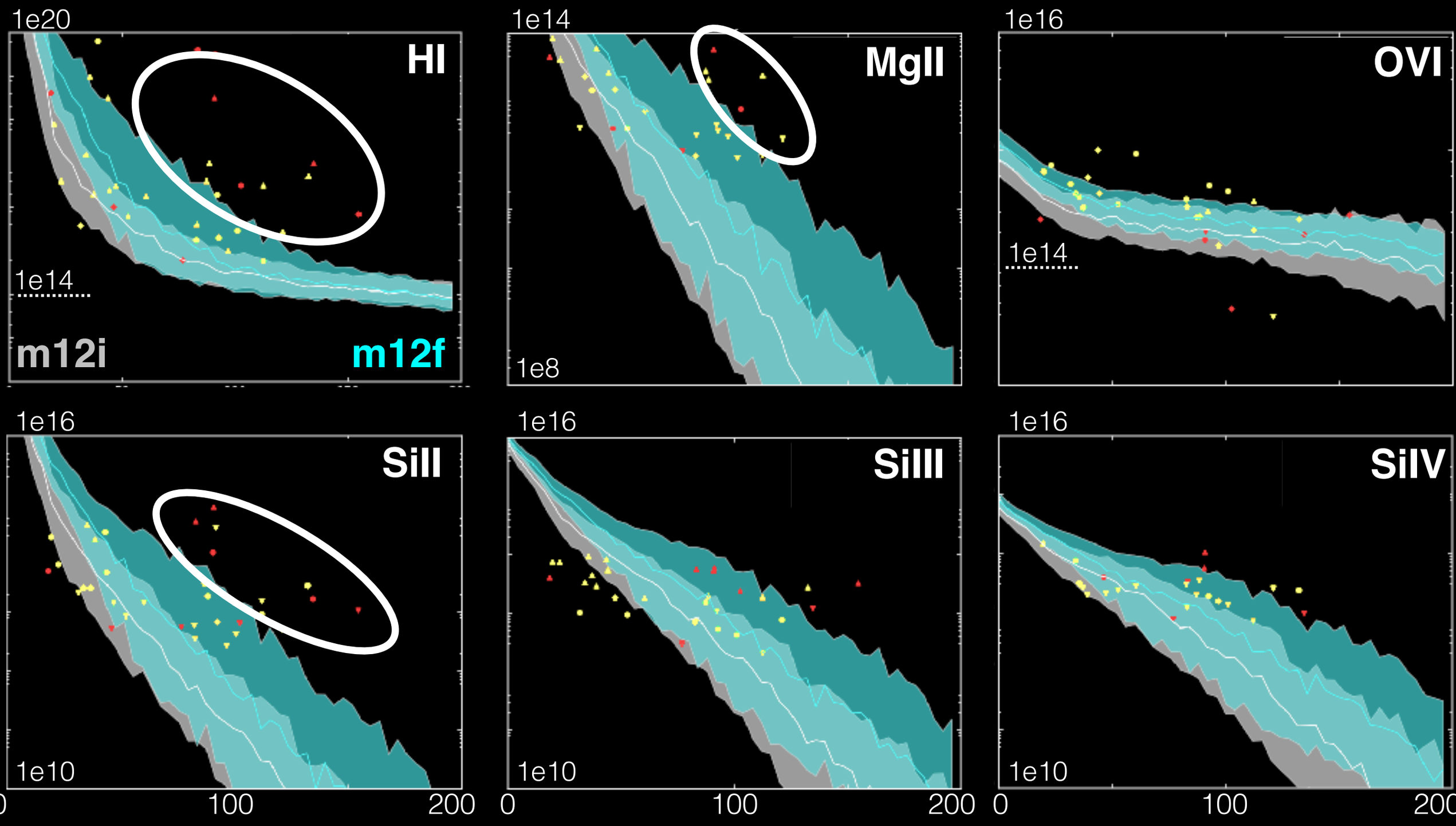




Dense, Low Ions at >100 kpc Still a Problem

BUT HIGH-IONS & LOW-DENSITY LOW-IONS EMERGING

Cameron Hummels (in prep)



What Worries Me?

Dust: Actual *Micro*-Physics

The Setup:

SQUIRE & HOPKINS '17 (SH; arXiv:1706.05020)

Gas equations = (anything that supports a linear mode)

Dust equations = continuity + momentum:

$$\frac{d\mathbf{v}_{\rm dust}}{dt} = -\mathbf{M}_{\rm coupling}\cdot(\mathbf{v}_{\rm dust}-\mathbf{v}_{\rm gas}) + \mathbf{a}_{\rm other}(...)$$

Arbitrary operator

e.g.

$$\frac{d\mathbf{v}_{\rm dust}}{dt} = -\frac{\mathbf{v}_{\rm dust}-\mathbf{v}_{\rm gas}}{t_s(...)} + \mathbf{a}_{\rm other}(...)$$

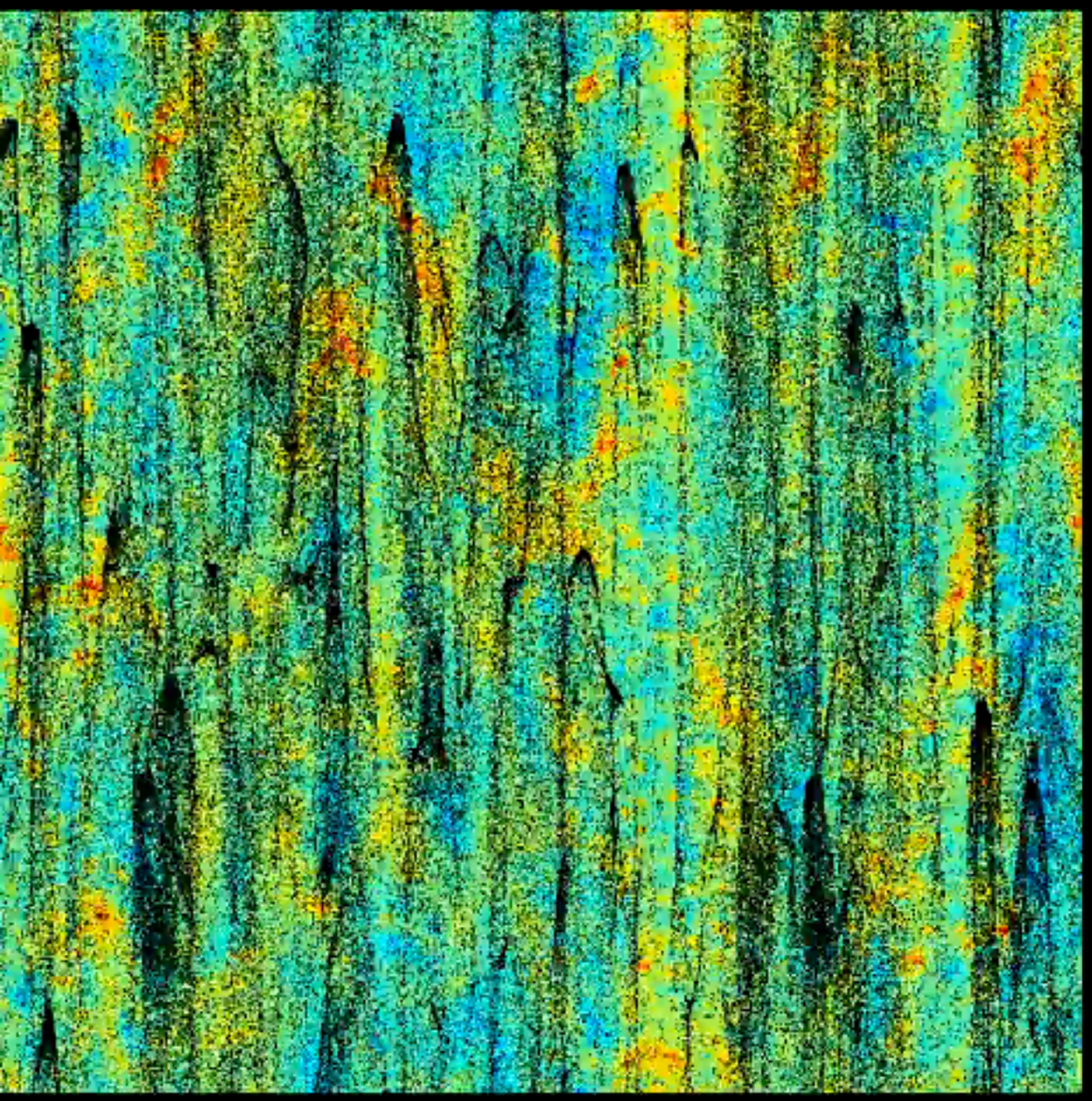
Stopping/drag time

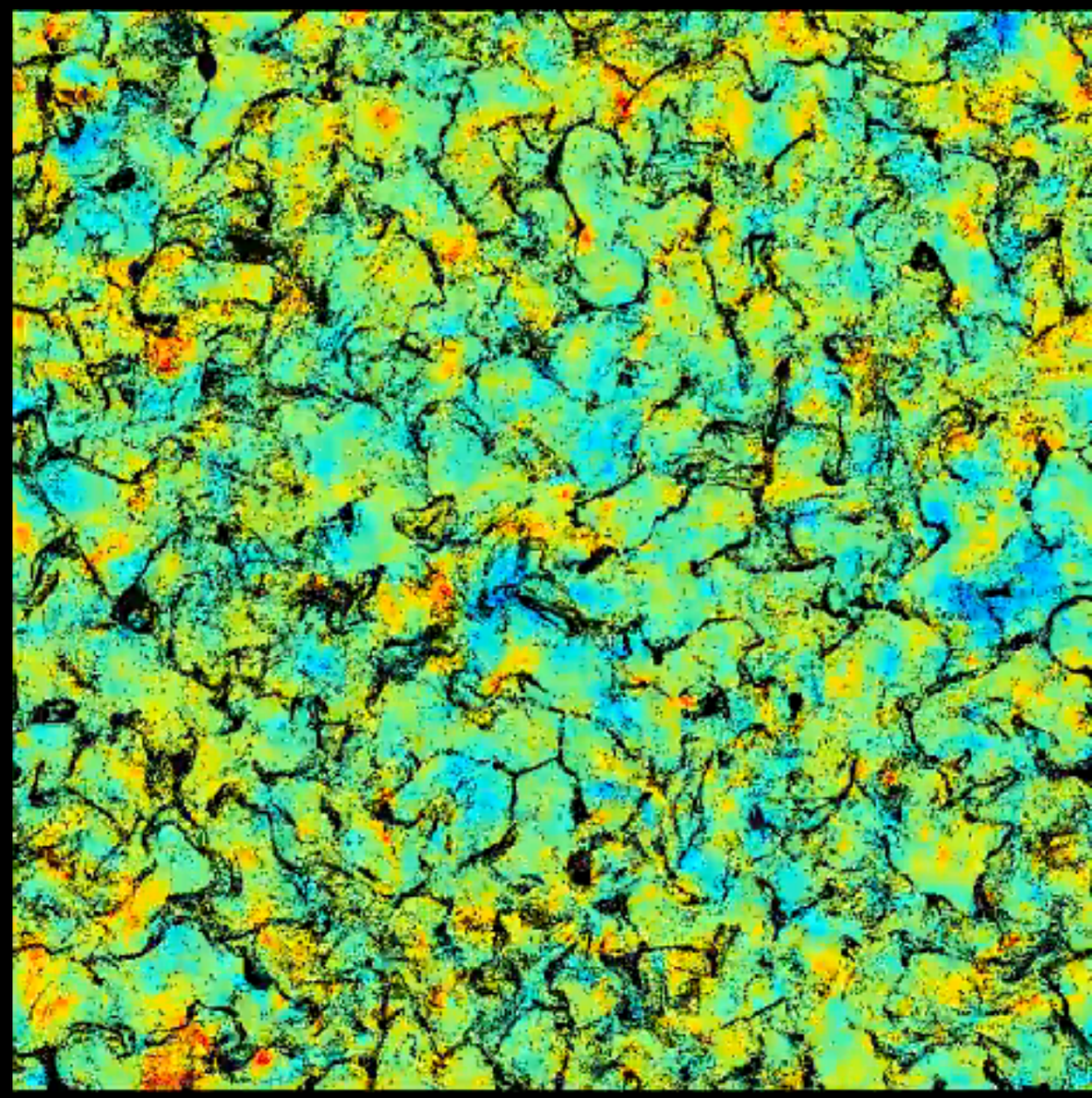
Jono Squire

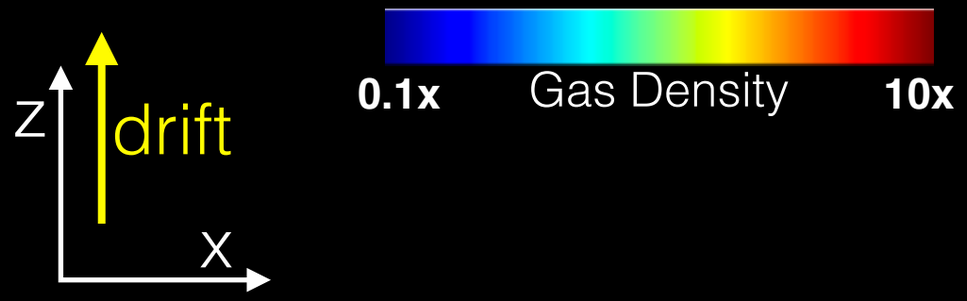
What Does This Look Like?
(TALK TO ME ABOUT NUMBERS)

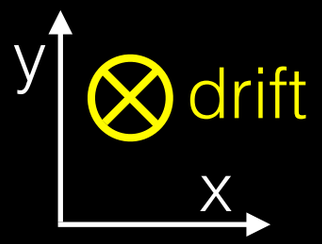
$|\mathbf{w}|_{\rm drift} \approx 10\,c_s$

$L_{\rm box} \sim 100\,c_s\langle t_s\rangle$ $\Delta t \sim 80\,\langle t_s\rangle$





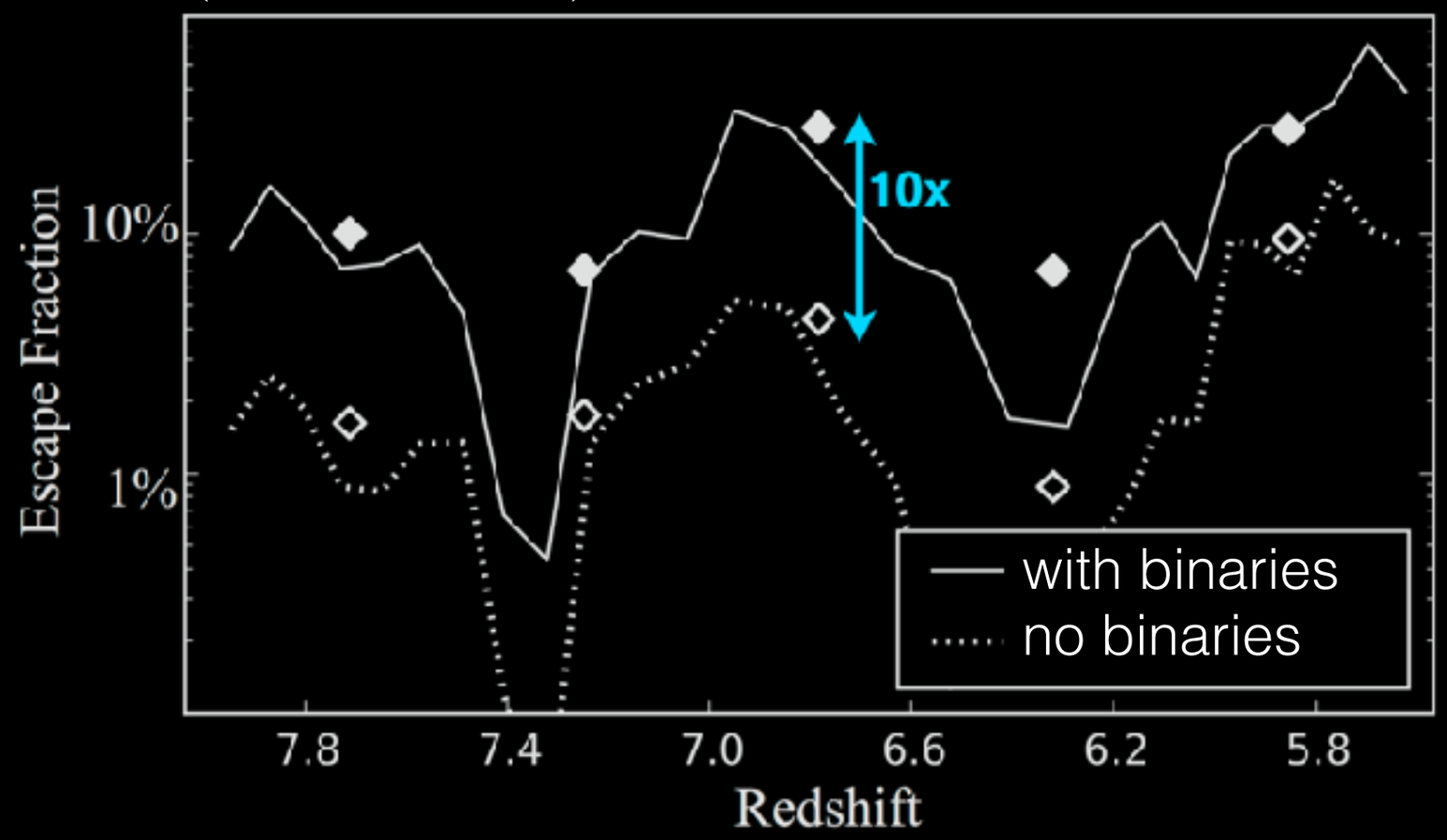


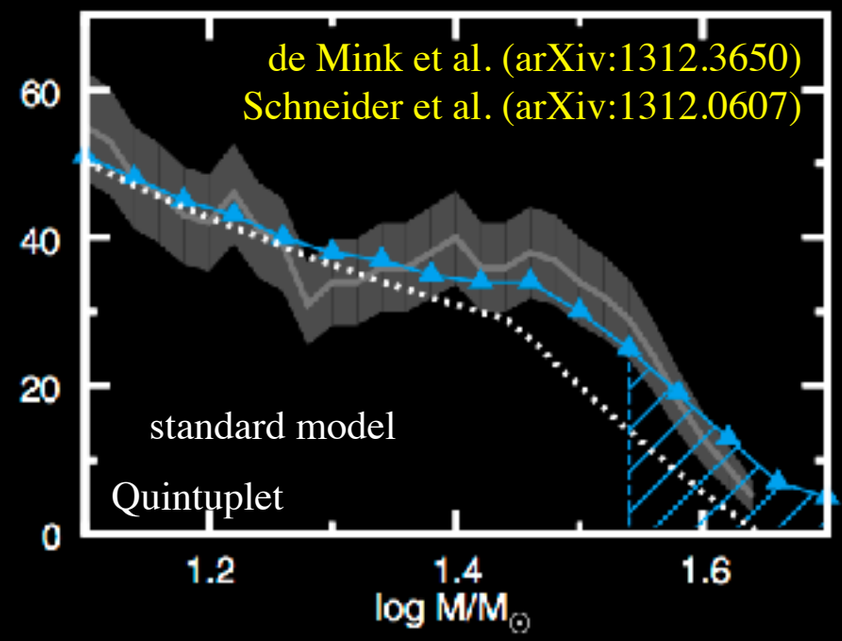


Binaries & Stellar Evolution

Binarity
IT MATTERS

Xiangcheng Ma
(arXiv:1601.07559)

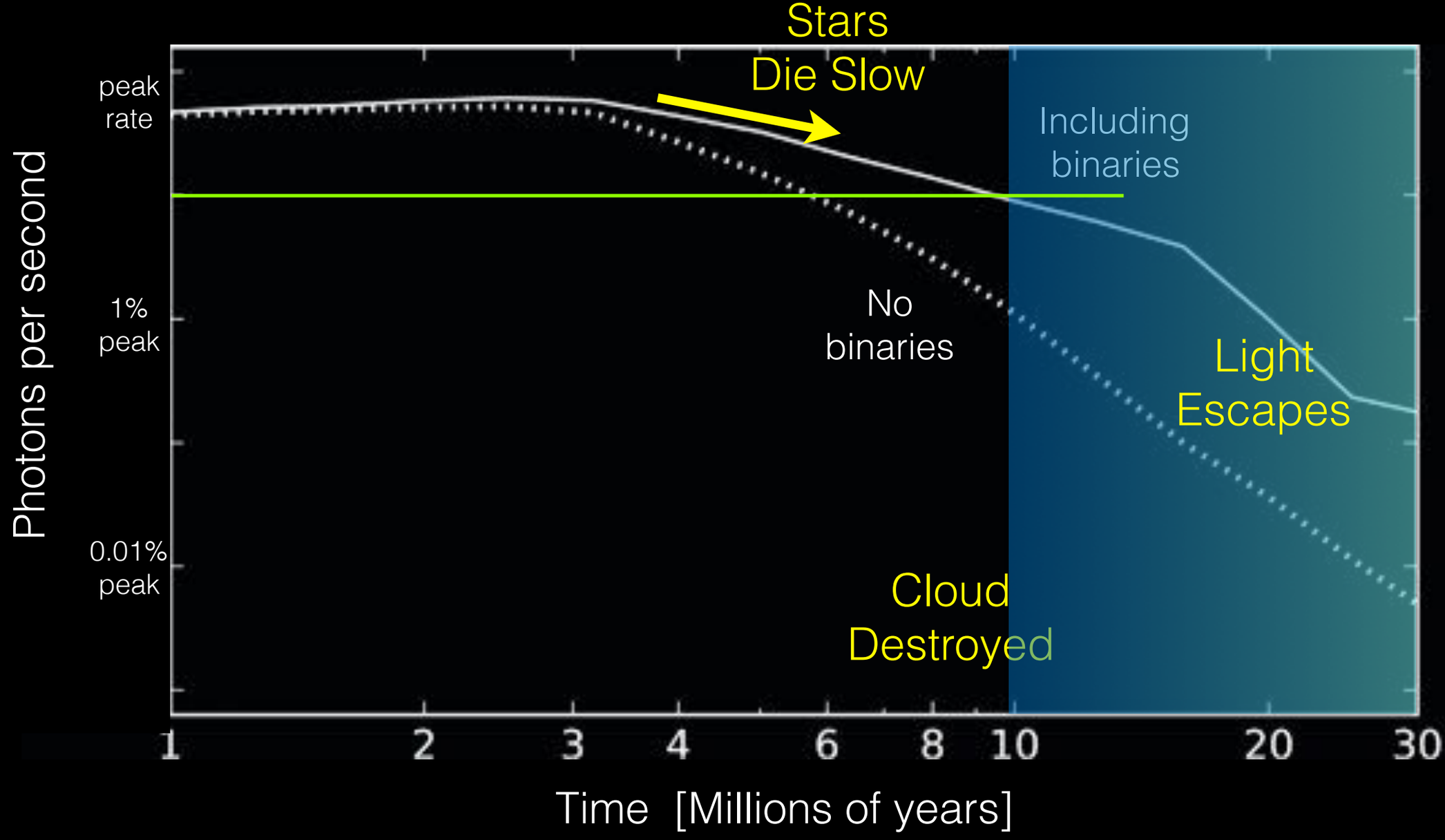




- GC abundances?
- Escape fractions
- IMF & massive stars
- Galaxy dynamics / masses
- High-z galaxy metallicities
- LIGO massive mergers
- Halpha as SFR indicator

Binary Stars:
THE ORIGIN OF THE "MISSING PHOTONS"

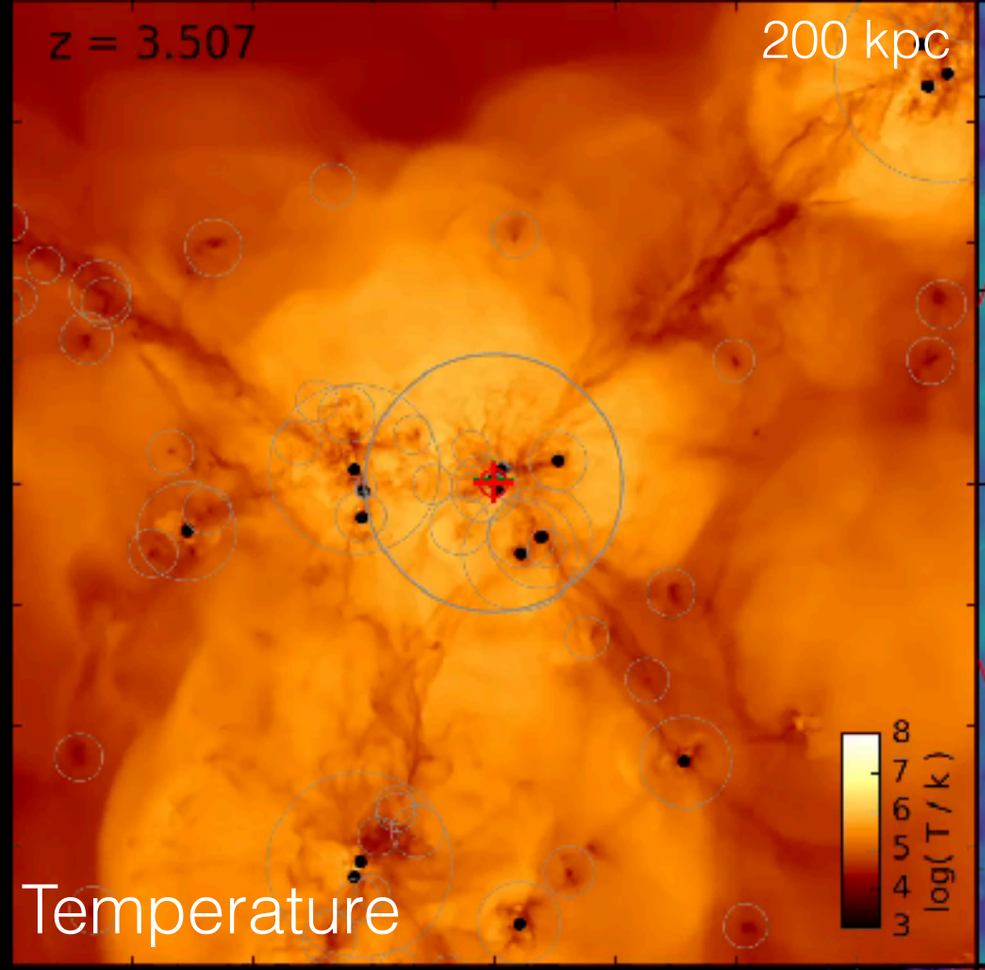
Xiangcheng Ma
(arXiv:1601.07559)

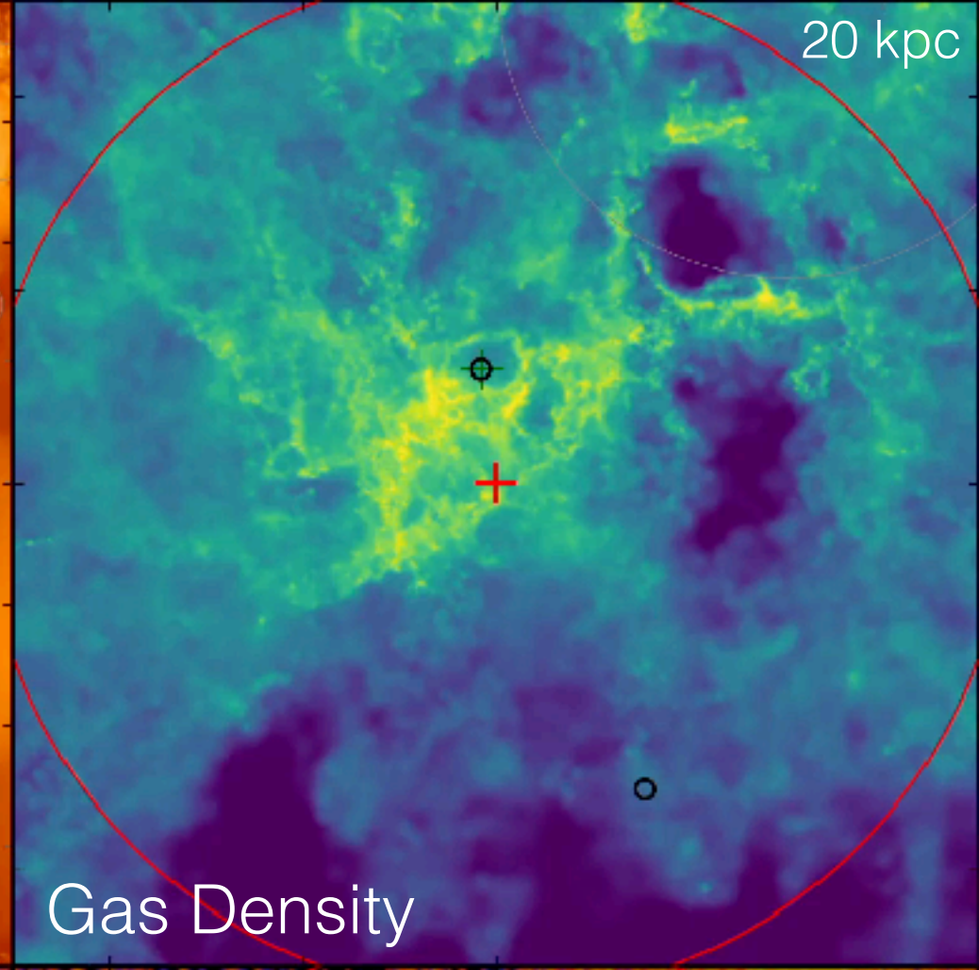


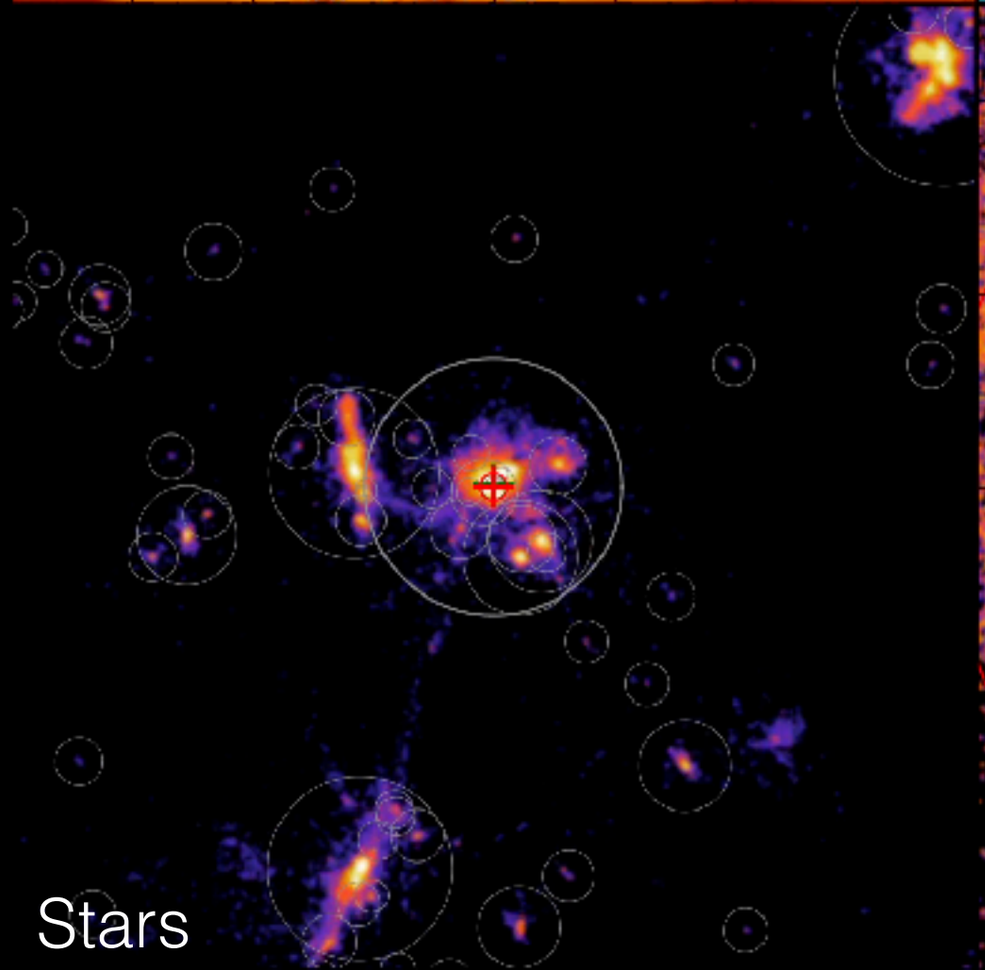
Simulation: ~20% escape!

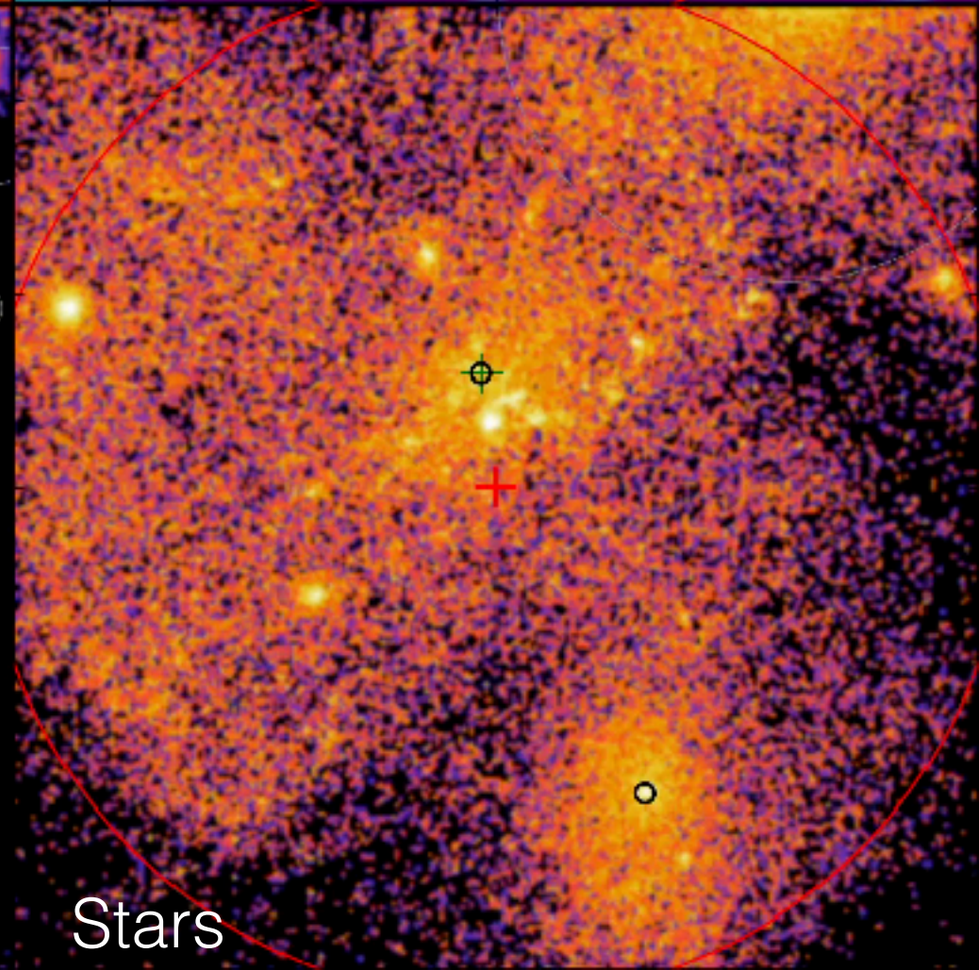
AGN?

Lumpiness + SNe
Need big seeds
or “anchors”





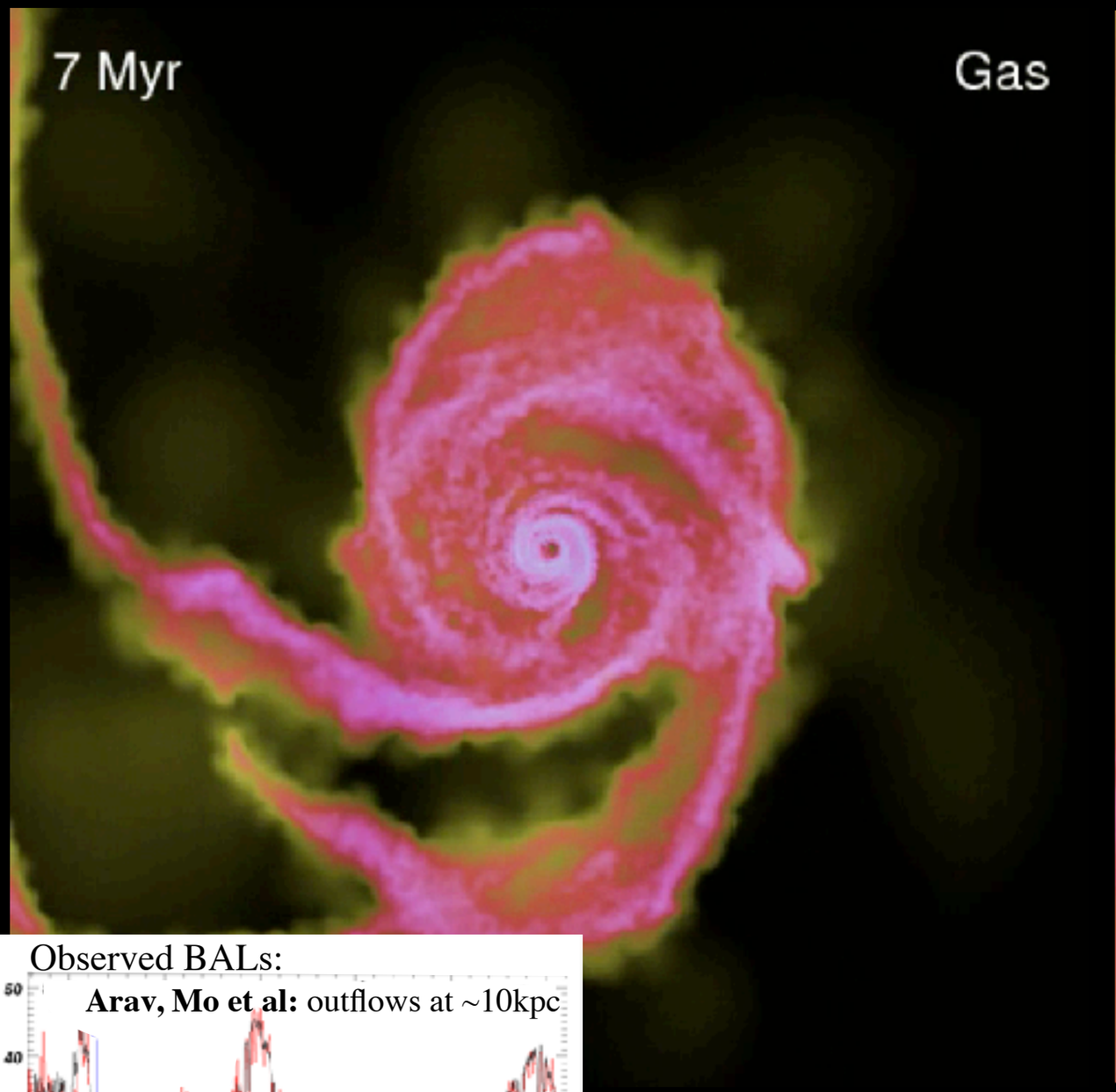




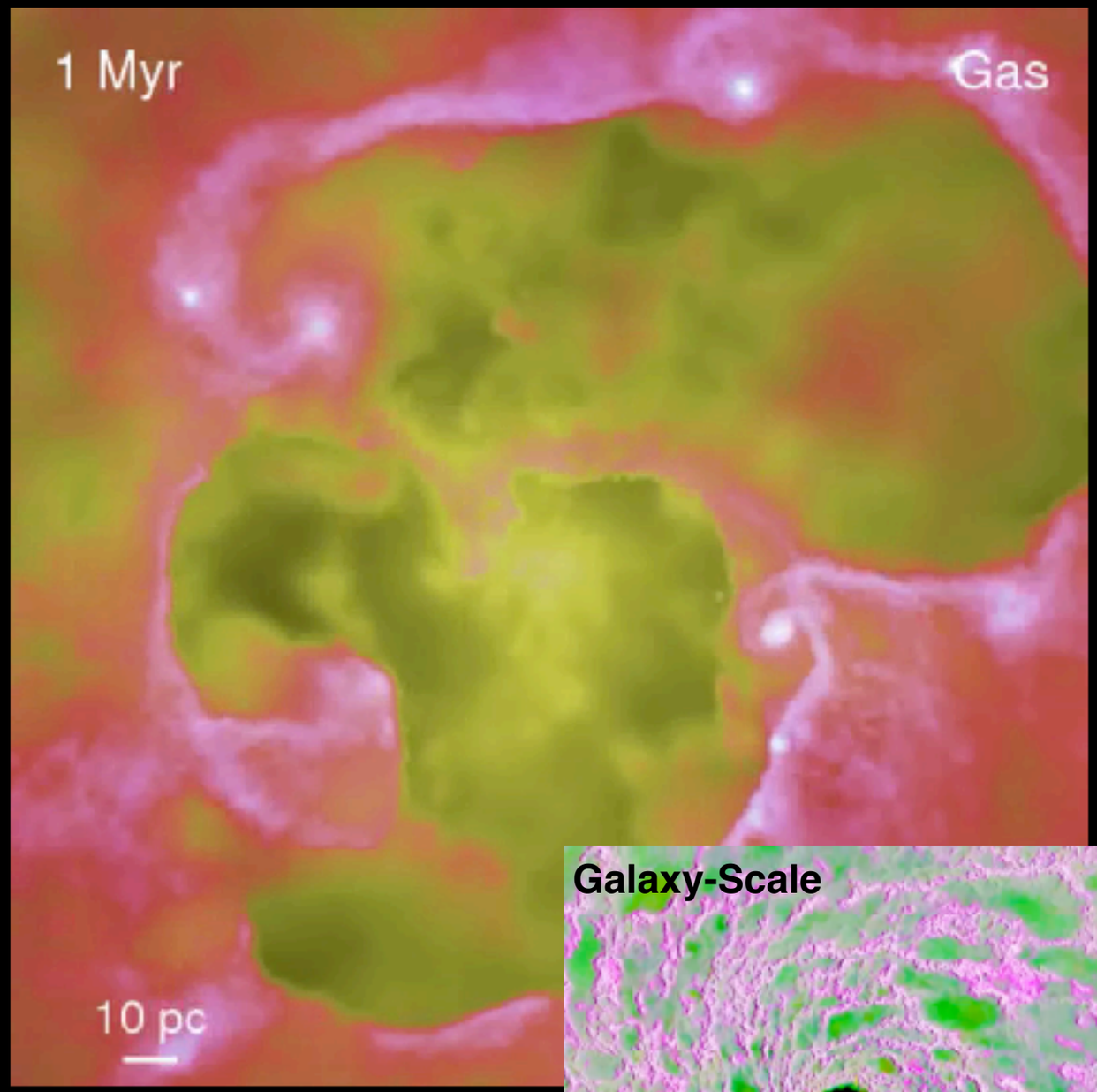
D. Angles-Alcazar
arXiv:1707.03832

Accretion Disk Winds: 0.01-10,000 pc

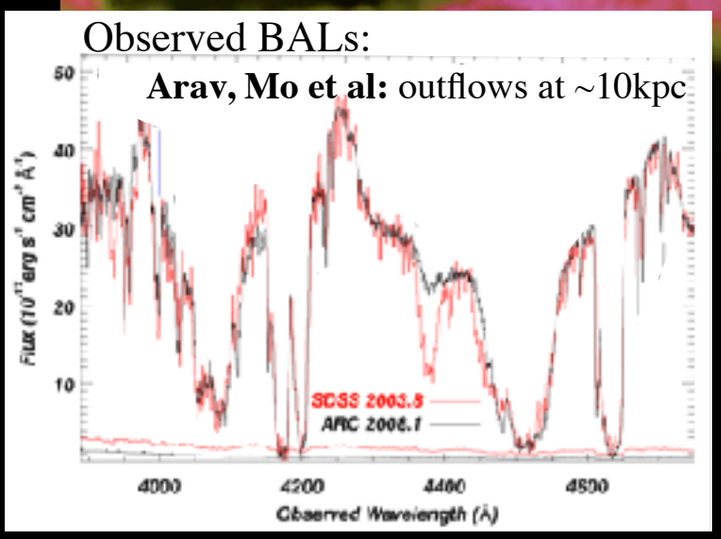
No BAL Winds



With BAL Winds

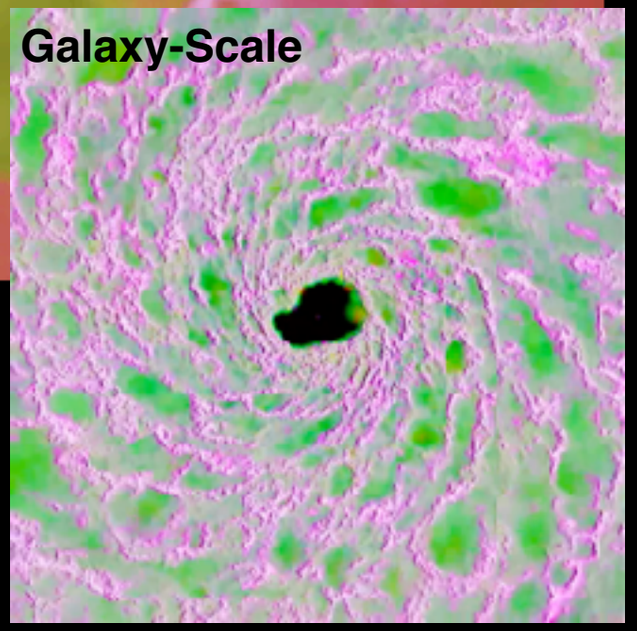


Observed BALs:



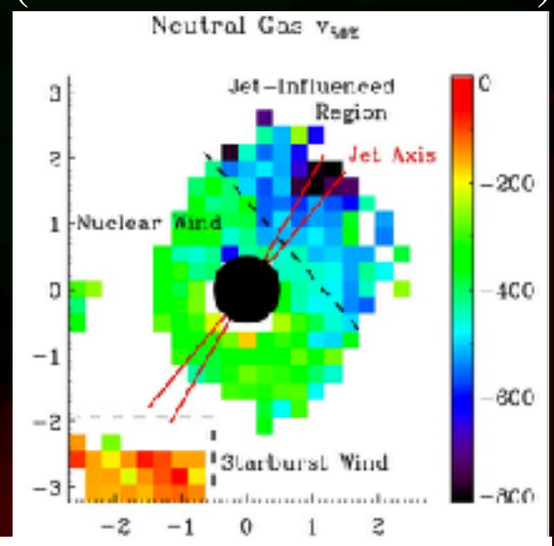
$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

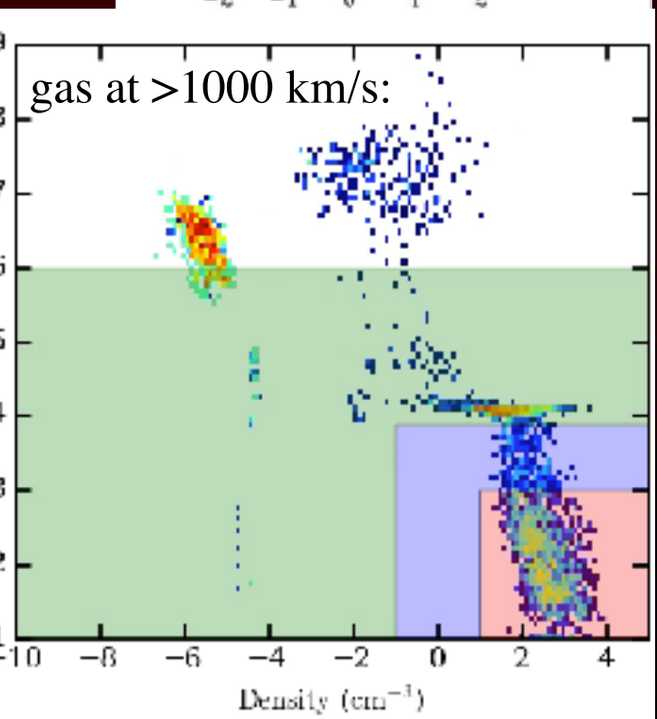
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$



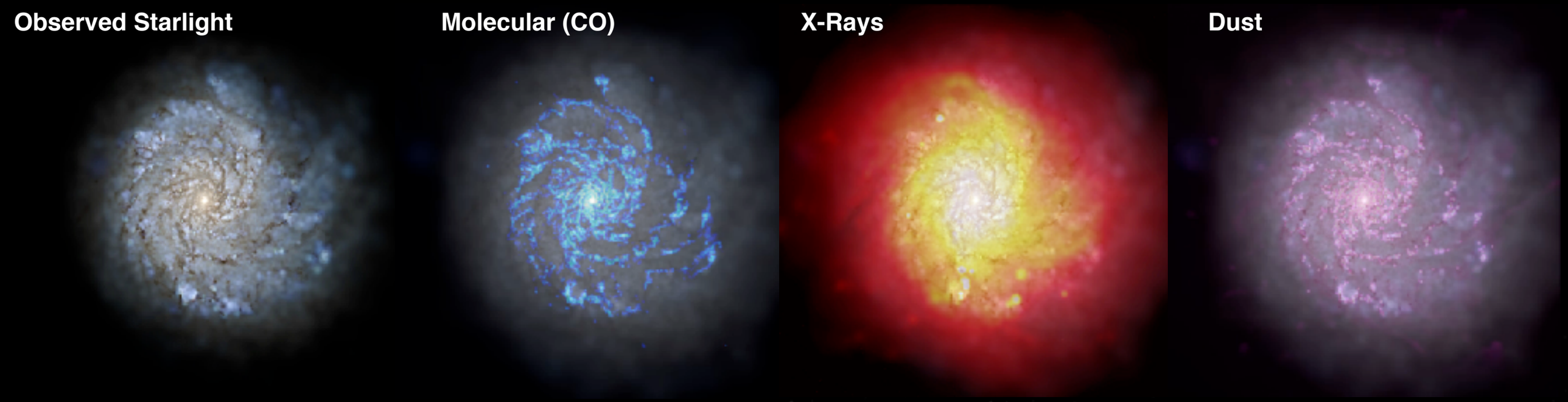
Accretion Disk Winds: 0.01-10,000 pc

Mrk 231
(+all other warm ULIRGs)





Torrey et al.
in prep



- Dust-Gas Mixtures Inherently Unstable (Squire+ 17)
- IMF: Feedback or Galaxy-Scale Models are Wrong (Guszejnov+ 17)
- Stellar clustering is Universal (Guszejnov+ 17)
- Realistic clusters: Cloud surface density determines properties (Grudic+ 17)
- Globulars resolved(?) (Kim+ 17)
- KS=feedback: dense laws; SF ‘starts’ with instability (Orr+17)
- Weak dependence of ISM/SF on MHD, etc (Su+ 17)
- Giant clumps ~ scaled GMCs (Oklopcic+ 17)
- Bursty SF important to observed SFR relations (Sparre+ 16)
- Bursty SF perturbs dwarfs (El-Badry+ 16), disk settling key (Ma+16)
- Halo structure (Sanderson+) & AGN (Torrey, Angles-Alcazar) in prep…

Galaxy Merger